

LATE PALAEOCENE – EOCENE TECTONO-SEDIMENTARY EVOLUTION OF  
NORTH WESTLAND, SOUTH ISLAND: AN ANALYSIS OF THE BRUNNER COAL  
MEASURES AND THEIR BASAL CONTACT

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# *Frontispiece*



A cold day on the Denniston Plateau, Buller Coalfield

## **Abstract**

The Late Palaeocene to Middle Eocene geological history of New Zealand is characterised by tectonic quiescence the development of an extensive unconformity. This period represents the time between cessation of spreading in the Tasman Sea Basin in the Late Palaeocene and commencement of extension of the Challenger Rift System in the Late Eocene. The unconformity itself and the Middle Eocene Brunner Coal Measures (BCM) which directly overlie it are used to study the tectono-sedimentary evolution of this time period in detail.

Field research has shown a deep leached horizon underlies the unconformity in almost all cases. This horizon formed through prolonged subaerial chemical weathering in the warm subtropical climate at this time. The degree of weathering is directly related to the duration of subaerial exposure but is occasionally enhanced through leaching of overlying coals. Truncation, partial or complete removal of the weathering profile indicates the presences of palaeovalleys and highs respectively.

Two occurrences of continuous deposition through the Late Palaeocene – Early Eocene are recognised. The Ikes Peak Formation and the Papahaua Formation, both within the Paparoa Group, are newly defined in this thesis. Both are related to faulting in the Late Palaeocene, potentially reflecting late stage tectonism related to the Tasman Sea spreading.

Stratigraphic columns created from measured sections across coastal North Westland have identified three distinct regions for the depositional history of the Middle Eocene Brunner Coal Measures (BCM). Deposition in the Greymouth Region predominantly records infilling of relict topography of the Late Cretaceous fault bounded basin in which the Late Cretaceous to Palaeocene Paparoa Group accumulated. The Middle Eocene time equivalent of the BCM is the near shore marine Island Sandstone. In the Buller Region, deposition is influenced by small scale syndepositional faulting and constitutes the thickest BCM. The remaining area between, the Charleston Region, is characterised by deposition related to marine transgression over a palaeohigh and the BCM here are thin, younger and often show hints of marine influence.

Palaeographic reconstructions were then used to produce a unified tectono-sedimentary model for North Westland which indicates strong NNE trending structural control and diachronous marine flooding. This suggests that the period of tectonic quiescence was not purely passive and that deposition of the Brunner Coal Measures records the initiation of the Late Eocene diffuse extension of the Challenger Rift System.

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# **Chapter 1 Introduction**

## **1.1. Introduction**

The Late Palaeocene and Eocene of North Westland in the South Island was a period of regional unconformity and the beginning of a major regional transgression (Nathan et al., 2002; Mortimer et al., 2014). This unconformity, typically at the base of the widespread Middle Eocene age Brunner Coal Measures, represents a time in Zealandia's otherwise active tectonic history where little, if anything was happening. Not until the Middle Eocene is there any indication of tectonic rejuvenation occurring in the North Westland region and currently there is no sedimentary expression for the time prior.

The study of this unconformity and the overlying Brunner Coal Measures is important for gaining a better understanding of not only North Westland's geological history but also for greater New Zealand. Eocene quartzose coal measures, correlatives of the Brunner Coal Measures, are found across the country (Suggate, 1950). The unconformity at their base represents a period (10ma or greater) of quiescence between cessation of extension related to the Tasman Sea spreading in the Late Palaeocene (Weissel & Hayes, 1997) and inception of the Challenger Rift in the Late Eocene (Kamp, 1986a).

The nature of an unconformity though means interpretation of the time it represents is limited to the events before and after, and the surface itself. Such detailed examination of this unconformity has not been attempted previously, partly due to this fact, but also to the generally understudied nature of West Coast geology. The aim for this research was to provide the detailed history lacking for this unconformity, define any relationship to stratigraphy immediately below and above and culminate in a regional tectono-sedimentary evolutionary model for the North Westland region.

## **1.2. Location of Study Area**

The area covered in research was mostly restricted to the coastal (west) side of the Paparoa Ranges, but overall covers approximately 3500 km<sup>2</sup> of the North Westland region (figure 1.1). Outcrop locations eventually used within this thesis extend from the Grey River in the south to the Mokihinui River in the north. Several scattered coastal or near coast locations in the

foreland of the Paparoa Ranges were used and an additional outcrop and stratigraphic column on the east side of the Paparoa Ranges near Reefton was also included.

For such an expansive field area, subdivisions were necessary. Three sub-regions, outlined in figure 1.1, were defined based on stratigraphic similarities of sections and outcrop after the majority of fieldwork and initial interpretation had been completed. The Greymouth Region was defined due to the complexities regarding the basal contact in this area with the underlying Late Cretaceous-Palaeocene fault-controlled extensional basin of the Paparoa Coal Measures. The Buller Region was identified primarily on the thick and fault controlled succession of Brunner Coal Measures (BCM) there. And the Charleston Region was grouped because it contains younger and far thinner BCM typically deposited later and lacking obvious fault control. The reasoning around area subdivisions is discussed further in the introduction section of each corresponding chapter.

#### 1.2.1. History of Research

The earliest studies and publications of North Westland's geology were made in the late nineteenth and early twentieth centuries in numerous bulletins of the New Zealand Geological Survey. McKay (1895), Bell (1906), Morgan and Bartrum (1915), Henderson (1917; 1929), Wellman (1950), Gage (1952) and Suggate (1957) document the geology of North Westland and form the basis on which all following work was based.

In the last 40 years a significantly greater amount of research has been conducted in the North Westland region. Of importance to this research are the advancements made in detailed geological mapping and the many 1:63,360 and 1:50,000 scale maps published by GNS (formerly NZGS) since the 1970's (Nathan, 1975; 1976; 1978a; 1978b; 1996; Laird et al, 1988; Rattenbury et al., 1998; Suggate et al., 1999; Nathan et al., 2002).

Other research has been either focused on the basement geology (Ghisetti et al., 2014), core complex formation (Ring et al., 2014), Cenozoic intrusives (Mortimer et al., 1999), hydrocarbon characteristics and resources (Nathan, 1972; Norgate, 1997; Moore et al., 2006) and a small amount of stratigraphy and basin analysis (Kamp et al., 1996; Bassett et al., 2006; Riordan et al., 2014).

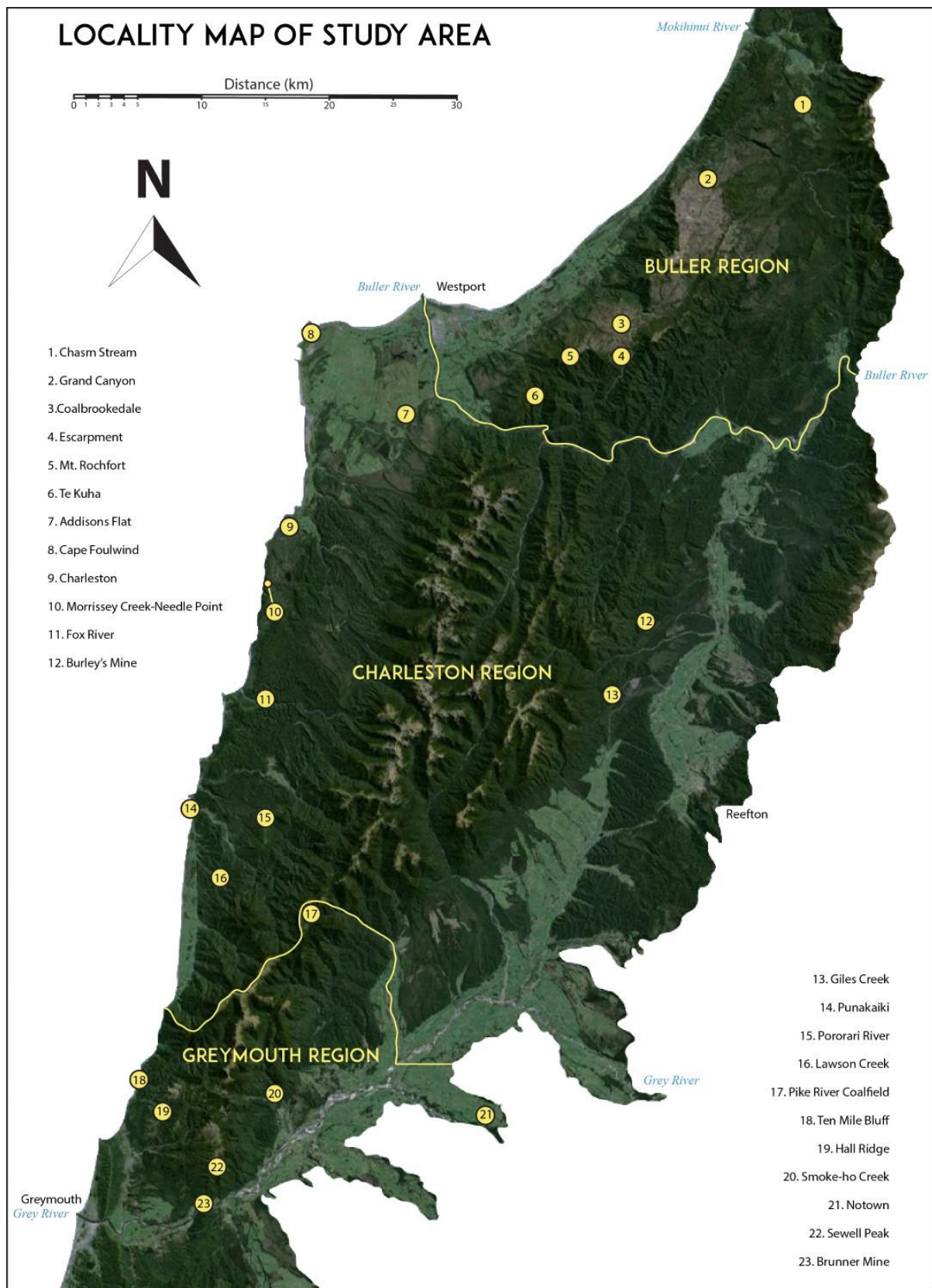


Figure 1.1: Locality map of the study area including the regional subdivisions, the Paparoa Range is the major mountain range in the Greymouth and Charleston regions while the Papahaua Range is the continuation north of the Buller River.



Unsurprisingly, with coal mining having been a prominent industry for over 100 years now, there is a significant interest in coal bearing strata. As such, most of the research relating to sedimentology is focused around the coals and often located within either the Buller or the Greymouth coalfields (Nathan, 1975; Newman, 1985; Newman & Newman, 1992; Titheridge, 1993; Flores & Sykes, 1996; Ward, 1996; 1997; Nunweek, 2001).

### 1.2.2. Thesis Structure and Chapter Organization

This thesis predominately focuses on sedimentology and stratigraphy of the Late Palaeocene – Eocene strata of North Westland. As such there is a significant amount of sedimentary description and interpretation documented within. To avoid an unnecessarily lengthy section on the sedimentology of the entire region, the chapters on sedimentology are arranged according to the subdivisions outlined in figure 1.1. These chapters, Greymouth, Buller and Charleston regions respectively, detail the sedimentary facies, depositional processes and chronology of the lower Cenozoic succession to provide a localized regional interpretation of the stratigraphy. The interpretations from these three areas are then incorporated into a unified depositional and tectonic history for the entire study area in the following discussion chapter.

## 1.3. Regional Geology

With over a century of research in the North Westland region, the geological history is well constrained. The region has been dominated since the Cretaceous by the separation of New Zealand from Gondwana and post rift drifting (Laird, 1994). More recent convergent processes along the modern day plate boundary have often overprinted much of the older history since the Miocene and the regional geology is generally complex (Nathan et al., 2002). A general overview of coastal North Westland's stratigraphy is illustrated in figure 1.2 and summarized below.

### 1.3.1. Palaeozoic

The oldest rocks encountered in the study area are the metasedimentary Greenland Group sandstones and argillites of the Buller Terrane (Rattenbury et al., 1998; Nathan et al., 2002).

This terrane represents an Ordovician sequence of deep water turbidites and pelagic shales (Roser et al., 1996) accreted to the Gondwana-Pacific margin. The Greenland Group is highly deformed with three distinct periods of deformation recognized (Jongens, 2006). It is also intruded by Devonian Karamea Suite Granites and later by the Mid Cretaceous Rahu Suite (Nathan et al., 2002).

### *1.3.2. Gondwana Margin and Mid Cretaceous Extensional Basins*

Up until 105 Ma, the Gondwana-Pacific margin was dominated by a convergent plate boundary subduction zone. At 105 Ma subduction abruptly halted and the Gondwana margin entered an extensional regime (Laird & Bradshaw, 2004). This is indicated by the formation of Metamorphic Core Complex's and associated extensional half graben basins throughout Zealandia (Laird, 1994). The Charleston Metamorphic Group and Mid Cretaceous Pororari Group represent these features in the North Westland region (Nathan et al., 2002).

The Paparoa Metamorphic Core Complex, one of several complexes in Westland, cuts directly through the study area roughly in accordance with the shape of the Charleston region (figure 1.1). This structure is oriented in a NW direction with a shallow dipping southern detachment (Pike) and a steeper northern detachment (Ohika) (Ring et al., 2014). Above these detachments, sedimentary half graben basins formed coeval with exhumation of the core complex and are represented by deposition of the Pororari Group (informally referred to as the Hawks Crag Breccia, the HCB is technically a formation within the group). The Pororari Group consists of sedimentary breccia's, conglomerate, sandstones, mudstone and minor coal (Nathan, 1985a; Laird, 1988) and forms the oldest terrestrial deposited in the study area.

### *1.3.3. Tasman Sea Opening and Late Cretaceous Extensional Basins*

Following the cessation of core complex and extensional half graben basin formation, there was a break in active extension until opening the Tasman Sea was initiated some 20-25 Ma later. Sea-floor magnetic anomalies show that spreading in the Tasman was most active from 82 Ma to 60 Ma (Weissel & Hayes, 1997) but that spreading did not completely cease until around 52 Ma (Gaina et al., 1998).

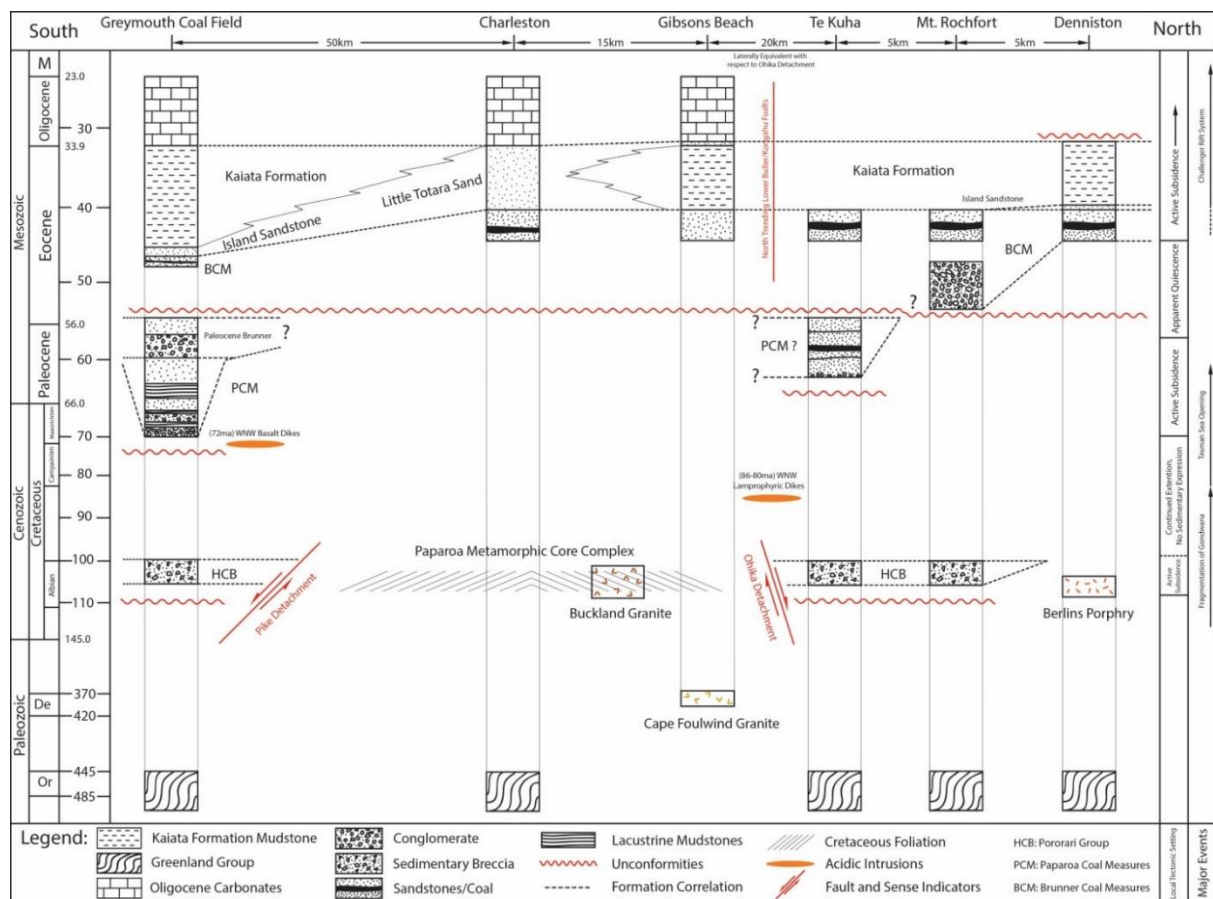


Figure 1.2: Chronostratigraphic transect for coastal North Westland's regional geology up until the Oligocene. (Based on the work of Newman, 1985; Nathan et al., 1986; Wellman et al., 1981; Laird, 1994; Flores & Sykes, 1996; Mortimer et al., 1999; Ring et al., 2014; Riordan et al., 2014)

Associated with the opening of the Tasman Sea was the formation of new NNE trending fault bounded continental extensional basins and subsequent deposition of the Paparoa Group during the Late-Cretaceous (figure 1.2)(Laird, 1994). The Greymouth and Pike River Coalfields contain the majority of exposed Paparoa Group strata in the study area with only minor fault bounded slivers exposed in the ranges behind Punakaiki. With the end of major spreading at c. 60 Ma, sedimentation in these basins ceased almost immediately and unconformities began to develop on the basin surfaces (Newman, 1985). Specific details relating to the stratigraphy of the Paparoa Group and an in depth history is included within Chapter 3 on the Greymouth Region.

#### *1.3.4. Eocene Brunner Coal Measures*

The Brunner Coal Measures (BCM) constitute the typical basal Cenozoic unit over much of North Westland. With the noted exception of the Paparoa Group, the BCM unconformably overlies Ordovician metasedimentary Greenland Group, the exhumed lower crustal equivalent the Pecksniff Paragneiss, Karamia and Rahu suite intrusive rocks, Mid Cretaceous Pororari Group breccias and sandstones and scattered basalt and lamprophyre dikes of varying Cenozoic ages (Rattenbury et al., 1998; Nathan et al., 2002). With the Paparoa Group, only a c. 10 Ma period separates the deposition of the BCM. Relict topography of the earlier basins has influenced deposition of the BCM in the Pike River and Greymouth Coalfields and the unconformity between the two can be difficult to recognize (Nathan 1978; Newman, 1985; Nunweil, 2001).

The BCM are generally comprised of coarse sandstones and interbedded carbonaceous siltstones and mudstones. They of course also contain thick low ash, but usually high sulfur coal seams, (Nathan, 1972; Norgate et al., 1997; Moore et al., 2006) typically in one or two main seams (e.g. Buller Seam Member, Mangatini Seam in the Buller Coal Field and the Brunner Seam in the Greymouth Coalfield). The majority of the BCM were deposited by meandering rivers on large, low gradient surfaces, with the coals and fine grained sediments accumulating on the floodplains (Flores & Sykes, 1996). A wide variety of other facies, such as prograding deltas, estuaries and incised stream conglomerates are also found within the BCM, but typically of lesser quantity (Titheridge, 1993) and predominately at the top and bottom of the unit respectively.

A defining feature of the BCM is that they are distinctively quartzose. Often quartz content of the coarse sandstones reaches upwards of 90% (Newman, 1985; Flores & Sykes, 1996). Siliceous cements mean these beds can be very resistant to erosion, hence why the BCM commonly form bluffs, escarpments and uplifted plateaus (Nathan, 1996). The high proportion of quartz is attributed to chemical weathering and quartz enrichment of the sediment source. It has been suggested that the landscape at the time had been extensively subaerially weathered for some time prior to deposition during a period of peneplanation and production of a weathered quartzose residuum (Suggate, 1950)

The Brunner Coal Measures have been described as the lowest member of a regional transgressive sequence present through all of New Zealand from the Eocene to Oligocene. In Westland this was originally defined as the Rapahoe Group by Gage (1952) with the Brunner

Coal Measures later proposed as an included basal unit by Lever (1999). More recently, with the high level stratigraphic scheme introduced by GNS (Mortimer et al. 2014), the Rapahoe Group would now be classed as a part of the Zealandia wide transgressive Haerenga Supergroup spanning second-order cycles 2 and 3 of King et al. (1999).

#### *1.3.5. Eocene – Oligocene Marine Transgression*

The top of the BCM is in most cases classified as a transitional boundary into the near shore marine Island Sandstone or Little Totara Sand (Nathan, 1975; 1978; 1996; Laird, 1988). This transition is a reflection of continued regional subsidence and subsequent marine transgression through the end of the Eocene. For much of North Westland this transition occurred around the Middle Eocene (Bortonian-Kaiatan), but in the Greymouth Coalfield the Island Sandstone is significantly older, deposited during the early Middle Eocene (Porangan stage) (Raine, 1982).

Following transition to marine sedimentation, transgression continued until a maximum was reached in the Late Oligocene. Over this time the Island Sandstone and Little Totara Sand were gradually succeeded by muddy mid- to outer-shelf Kaiata Formation and in all but a few examples the Kaiata Formation is overlain by limestones of the Nile Group.

This transgressive sequence is related to a new period of E-W extension attributed to formation of the Challenger Rift (Kamp, 1986a). In the North Westland region the Paparoa Trough, a major extensional structure and part of the greater Challenger Rift system, is known to have had major control on deposition during the Late Eocene and into the Oligocene (Kamp et al., 1996; Norgate et al., 1997; Furlong & Kamp, 2013). The Paparoa Trough is also aligned with the Paparoa Tectonic Zone, a suggested interconnected array of faults that may have controlled deposition during the Late Cretaceous and Early Palaeocene (Laird, 1968; Lever, 1999). Currently though it is not known how much of an effect, if any, these structures had during deposition of the BCM.

#### *1.3.6. Miocene – Present, uplift in the modern transpressive plate boundary*

During the Miocene the change to the modern day convergent plate boundary is reflected by renewed clastic sediment deposition and the cessation of limestone formation (Nathan et al.,

2002). Continued compression uplifted, faulted and deformed the entire North Westland region and produced the complex geology present today.

#### **1.4. Scope and Objectives**

Previous research around the basal unconformity of the Brunner Coal Measures and the general history of North Westland for this time have been restricted mainly to studies on the coal measures themselves. Currently no studies have been attempted specifically focused on the unconformity itself or the time it represents, nor has the regional depositional history of the overlying BCM been assessed in detail. Such information would be beneficial in further understanding the Palaeocene-Eocene history of the North Westland region. Specifically the cessation of spreading of the Tasman Sea and associated extensional basins, the inception of the Challenger Rift and the intervening quiescent period.

The main objectives to of this thesis are therefore:

1. Describe and interpret the unconformity and the stratigraphy immediately above and below in the three main regions (figure 1.1), with a focus on detailed local landscape evolution.
2. Assess current stratigraphic divisions and revise the nomenclature where such re-division is needed.
3. Produce a series of paleographic reconstructions for North Westland from the Late Palaeocene to Middle Eocene, detailing the deposition of the BCM on a regional scale.
4. Incorporate new and existing sedimentological data into a unified tectono-sedimentary model for North Westland and discuss implications for the regional tectonic evolution of greater Zealandia.

To fulfill these objectives a predominantly sedimentological and descriptive approach will be used. Research will mainly focus on collection of new data through extensive field work throughout the region in addition to collation and reinterpretation of existing data. Where nomenclature and chronostratigraphy is concerned, the work of previous authors becomes very important. In such cases, typically only reinterpretations will be made.

## **Chapter 2 The Greymouth Region**

### **Influence of a pre-existing basin**

#### **2.1. Introduction**

The most southerly section of the field area, the Greymouth region, represents a sedimentary basin with a history of activity since the mid Cretaceous. In contrast to most other areas, the Palaeogene sequence is preceded by Late Cretaceous to Paleocene Paparoa Group sandstones, coals and lacustrine mudstones deposited in an extensional basin (also referred to as the Paparoa Coal Measures or PCM) (Gage, 1952; Newman, 1985; Nathan, 1978b; Nathan et al., 2002). The PCM are distinctively fault controlled with the upper units showing a clear NNE-SSW trend in isopach maps (Gage, 1952; Ward, 1997; Cody, 2015). The quartzose Middle Eocene Brunner Coal Measures or coeval near shore marine Island Sandstone overlie these older Cretaceous rocks (Newman, 1985), and likely initially deposited within the same basin that the Paparoa Group had accumulated in (Nathan & McKenzie, 1986).

The Greymouth Region in this thesis mostly refers the area of the Greymouth Coal Field. That is, the southern tip of the Paparoa Ranges to the north of the Grey River. Other outlying areas are also included within the greater Greymouth Region but the focus is primarily around the Greymouth Coalfield and the basin it represents (herein termed the Greymouth Basin).

The stratigraphy of the BCM and basal contact is complex and not well studied in the Greymouth Basin. The basal unconformity of Eocene age strata is often not distinguishable in the field and requires palynological dating to confirm its location (Newman, 1985; Nunweek, 2001). In addition, while the Brunner Coal Measures were originally defined here (Morgan & Bartrum, 1915), they are typically older than elsewhere and they have been classified in a variety of ways with different tectonic and stratigraphic connotations (Nathan & McKenzie, 1986; Nunweek, 2001). The overall tectonic history surrounding the upper Paparoa Group and the deposition of early Cenozoic strata in the region is also not well understood (Ward, 1997). These issues formed the basis for research in this region.

Investigations mainly focused on providing a stratigraphic cross section through the main areas of the basin. This was used to construct a stratigraphic and tectonic model that accounts for all previous and new observations and allows interpretation of the tectonic history during deposition of the upper PCM and BCM. Palynological dating from Newman (1985), Ward (1997) and the Fossil Record File Database (FRED) was used for age control and all existing

knowledge is incorporated into this unified stratigraphic and tectonic model. Re-examination of the stratigraphic nomenclature used by previous authors also became a key goal of work in the region. The primary aim of reclassification and interpretation is to deliver a lithology-based classification that will be mappable in the field and will clarify the stratigraphy and basin architecture.

## **2.2. Geologic and Nomenclature Background**

### *2.2.1. History of research*

With over 100 separate mines operated since 1862 (Gage, 1952), the Greymouth Coal Field has been extensively studied. Most of this research is in relation to the coals themselves but the general stratigraphy is also well documented (Gage, 1952; Ward, 1996). The first research and publications were made in the late nineteenth and early twentieth centuries. McKay (1893-4), Bell (1906), Morgan (1908; 1911), Morgan and Bartrum (1915) and Henderson (1917) progressively delineated the geology of the Greymouth Coalfield and surrounding areas into a sound stratigraphic framework. The Paparoa and Brunner Beds were defined over this time, the Paparoa Beds named after the Paparoa Ranges and the Brunner Beds after the coal and quartzose sandstones at Brunnerton (Morgan & Bartrum, 1915). These classifications formed the basis for further detailed investigations that followed.

Maxwell Gage, in an extensive exploration program of the Greymouth Coalfield, classified the Paparoa Beds into the modern divisions and the Brunner Beds to the Brunner Formation (Gage, 1952). At the same time, the work of Harold Wellman on the Paparoa-Brunner unconformity near Greymouth (Wellman, 1950) complemented the research undertaken by Gage. There was a lull for some time after with little research completed until Simon Nathan's work on the Greymouth Map Sheet (Nathan, 1978) and Jane Newman's PhD thesis (Newman, 1985) when more advances were made and the naming of the Brunner Coal Measures was formalized. More recently, Simon Ward (1997) completed a large PhD thesis on the lithostratigraphy, palynostratigraphy and basin analysis of the Paparoa Group including a revised nomenclature for the complex stratigraphy. Shortly after, Colin Nunweek (2001) added some new, but informal, stratigraphic subdivisions that are relevant to this research in an MSc thesis on the depositional controls on peat accumulation and coal characteristics of the upper Paparoa and Brunner Coal Measures. In addition to the academic research, there have been numerous exploration programs completed by various coal companies. The information gathered from



drilling during these programs is generally available, the older data being obtained online (NZPAM Online Exploration Database) while newer data is typically held by the operators (Solid Energy, Francis Mining, etc.)

### 2.2.2. *Paparoa Group*

The Paparoa Group (also Paparoa Coal Measures) are a Late Cretaceous to Early Palaeocene succession of fluvial and lacustrine rocks deposited within a fault bounded extensional basin(s) (Gage, 1952; Newman, 1985; Ward, 1997). The PCM crop out extensively in the Greymouth and Pike River Coal Fields but are also found in isolated fault bounded pockets and slivers in the ranges behind Punakaiki, small outcrops to the southeast of Hokitika and inland from Ross, and a fault bounded segment in northern Fiordland (Laird, 1988; Nathan et al., 2002). Within the Group, a number of subdivisions have been made which detail the generally alternating sequence of strata. The nomenclature surrounding these subdivisions has been classified and re-classified for over a century and is often confusing or has multiple alternatives. These classifications have been recently informally reverted to Gage's (1952) original nomenclature of a simple series of formations for ease of use (Cody, 2015). The Paparoa Group level of Nathan et al. (2002) is retained.

Pike River Coalfield currently does not adopt the subdivisions and nomenclature of the Greymouth Coalfield (instead relying on a series of numbered members), but Newman (1985) highlighted that both areas share similar a stratigraphy. Pike River is not discussed in detail but this fact is relevant for correlation of the Pike River and Greymouth Coal Fields.

The Paparoa Group began deposition around 72 Ma (Laird, 1992). For this research only the upper formation is considered important and only a simple overview of the lower formations are included. These formations are the Jay, Ford, Morgan, Waiomo, Rewanui, and Goldlight Formations, the Jay Formation at the base and the Goldlight Formation at the top. The Jay, Morgan and Rewanui Formations are typically composed of coarse channel sandstones, floodplain siltstones, often thick coals and occasional conglomerates which are interpreted as meandering river floodplain and delta facies (Gage, 1952). The Ford, Waiomo and Goldlight Formations are generally fine grained sandstones, siltstones or mudstones deposited in a lacustrine setting (Cody, 2015). The far east of the coalfield differs from this generalized overview and conglomerates dominate Morgan Formation. This is also the case in the northwest where the Rewanui Formation is also composed of conglomerate.

The upper most formation, the Dunollie Formation, is typified by channel sandstones and alternating siltstones, fine sandstones and coals of a typical floodplain setting (Newman, 1985; Nunweek, 2001). In the northwest of the coalfield the Dunollie Formation is also dominated by an alluvial fan conglomerate (Gage, 1952; Newman, 1985). The upper contact of the Dunollie though has been variably defined since it was first conceived. Currently the last carbonaceous horizon is used to define the upper boundary of the unit (Ward, 1997).

The orientation and tectonic history of the Greymouth Basin has been derived primarily from isopach models of these formations. Gage (1952) was the first to suggest that the basin has experienced two distinct stages of extension. The oldest units, the Jay Coal Measures and Ford Siltstones, were deposited in a basin oriented WNW suggesting N-S extension. The younger units, the Rewanui, Goldlight and Dunollie Formations, were deposited in a NNE oriented basin suggesting E-W extension. The Morgan and Waiomo Formations record the transition in basin orientation. An abrupt truncation of the Paparoa Group by the Roa - Mt Buckley Fault Zone in the east has been used as evidence for fault control on that side of the basin (Ward, 1997), despite the lack of sedimentological data to support this claim (Cody, 2015; Suggate, 2014). Nevertheless this initial interpretation has been accepted by all subsequent authors (Nathan, 1978; Newman, 1985; Ward, 1997; Nunweek, 2001 and many others).

The trouble with this interpretation is that the use of isopach models for the current unit thicknesses and disregard for sedimentological aspects has resulted in a model that is likely incorrect. Emma Cody (2015), on reexamining the lacustrine formations of the Paparoa Group, constructed new isopach models which suggest that no change in basin orientation occurred and that the basin was controlled by faulting to the west, for its entire history with only minor faulting to none, in the east. This new interpretation is used for the tectonic history of the Paparoa Group in the Greymouth Coalfield.

### *2.2.3. Brunner Coal Measures and Palaeocene Brunner Formation*

Above the Dunollie Formation there is a prominent conglomerate grading into a quartzose sandstone. The conglomerate is similar to the Dunollie Formation conglomerate at the coast and was originally included within that formation. The quartzose sandstone at the top was defined as the original Brunner Coal Measures, named after the outcrop of the unit in the Grey River at Brunnerton. This classification remained until palynological dating by Raine (1982) identified that the quartzose coal measures in the center of the coalfield were Late Palaeocene

(Teurian) in age, as opposed to the Middle Eocene (Bortonian-Kaiatan) Brunner Coal Measures elsewhere (Couper, 1960; Nathan, 1978b). This observation prompted Nathan & McKenzie (1986) to classify these rocks as the Brunner P (a Palaeocene equivalent to the BCM), but not until Nunweek (2001) was a complete nomenclature outlined to account for these Palaeocene age ‘Brunner like’ rocks.

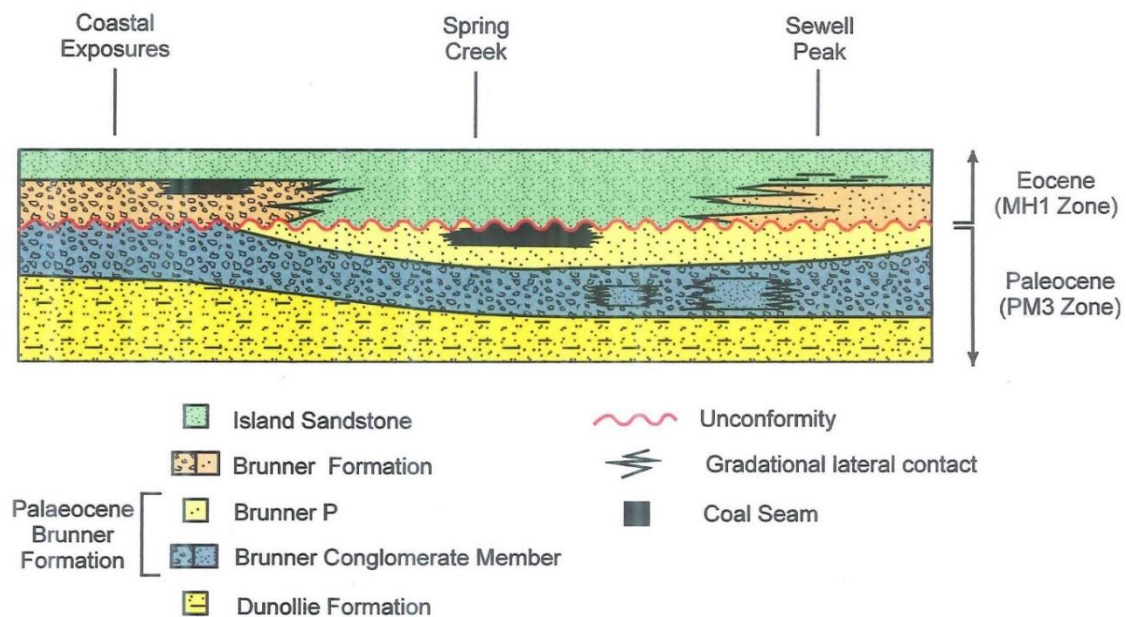


Figure 2.1: Lithostratigraphic summary of the Palaeocene Brunner Formation (Nunweek, 2001). East-West orientation correlates approximately with the right and left sides of the diagram.

Nunweek’s (2001) proposal included the creation of a new formation; the Palaeocene Brunner Formation (PBF) for a localized subdivision of the coalfields stratigraphy. This formation replaces the Palaeocene age Brunner Coal Measures in the center of the coalfield and also included the upper Dunollie Formation conglomerate. At the coast and to the east of the coalfield at Blackball, Middle Eocene (Bortonian) Brunner Coal Measures are present (Couper, 1960; FRED). This means that the PBF is restricted the confines of the Greymouth Coalfield.

Two members were also classified within the PBF. The Brunner Conglomerate Member represented the polymict grading to quartzose conglomeritic facies that were previously grouped as part of the Dunollie Formation. This member begins at the last/upper carbonaceous horizon in the Dunollie Formation (Ward, 1997; Nunweek, 2001). The transition at the top of

the Brunner Conglomerate Member is arbitrarily placed where the conglomerate grades into quartzose sandstones. These sandstones were named the Brunner P Member, retaining the earlier classification of Nathan and McKenzie (1986). The top contact of the Brunner P Member can be difficult to locate in the field. In some places it is marked by a coal seam and others by a burrowed and silicified surface. In coastal exposures Middle Eocene Brunner Coal Measures may also rest directly on the Brunner Conglomerate Member and no Brunner P Member is present (figure 2.1).

This top contact though represents a significant unconformity. Palynological dating (Raine, 1982) revealed that at least c.8 Ma are represented by this unconformity, in places being accommodated with the coal itself. Despite the ambiguous nature of the contact, it still represents a long period of time.

### *3.2.3 Island Sandstone*

Above the Palaeocene Brunner Formation and the unconformity is the Middle Eocene (Bortonian) Island Sandstone (Raine, 1982; Newman, 1985), or less commonly Middle Eocene (Bortonian) age Brunner Coal Measures (Couper, 1960). The Island Sandstone is typically a yellowy, flat bedded, glauconitic, calcareous, fine sandstone or siltstone, often with no internal structure (Nathan, 1978b). It is often fossiliferous and has been interpreted to have formed in a near shore shallow marine setting (Gage, 1952; Nathan, 1978b). However, at the very base of the Island Sandstone in the center of the coalfield, there are coal seams and carbonaceous laminations. These are indicative a more costal environment, possibly as part of an estuary, delta or lagoon but are considered to be part of the Island Sandstone based on the visual similarities and calcareous nature (Newman, 1985).

## **2.3. Methods**

Three key areas were used to represent the Greymouth Coalfield with several outlying areas also of importance for interpretation of the region's depositional history. These three areas, the northwest sector, the central coalfield and the eastern flank broadly represent the coastal exposures, the central basin stratigraphy and the hinterland areas respectively.

These areas were chosen based on the work of previous authors and the importance the respective areas have in regards to the basin interpretation. Measured type sections of Newman (1985), descriptive accounts of Wellman (1950), Gage (1952) and Nathan (1978b) and palynological dating of Couper (1960) and Raine (1982) were key in identifying these areas.

Detailing the stratigraphy of these key localities included both reexamination of previous work and measuring new sections. In the case of the central coalfield this was achieved with both revisiting and reinterpreting the already established type sections and adding more detail where necessary. For the northwest sector and the eastern flank new sections were measured where outcrop would allow. Methods included clast counting, bedding orientation measurements and in the northwest sector point counting of thin sections to determine compositional variation.

Many of the interpretations made from these sections are based on established ideas made by previous workers. Where interpretations vary between those made here in and those of previous workers, all relevant reasoning is documented either in text, or in the corresponding stratigraphic columns.

## **2.4. Key Sections**

### *2.4.1. Central Coalfield*

The section at Birchfield Opencast Coal Mine has been chosen to be the type section for the Palaeocene Brunner Formation and represents the central coalfield. The section at Birchfields Opencast Coal Mine down the eastern slope towards Spring Creek is one of two sections that have previously been palynologically dated as part of Jane Newman's (1985) PhD thesis and identified the difference in age of the quartzose coal measures of the Greymouth coalfield with respect to the rest of the West Coast. The original stratigraphic column presented within Newman's (1985) thesis was deemed to be of exceptional quality when investigated in the field and did not require re-measuring of the section. Instead it has been redrawn to conform to the style used throughout this thesis. The sedimentological details are however my own work unless specifically stated be from Newman (1985). The section has also been re-interpreted with a greater focus on these sedimentological aspects.

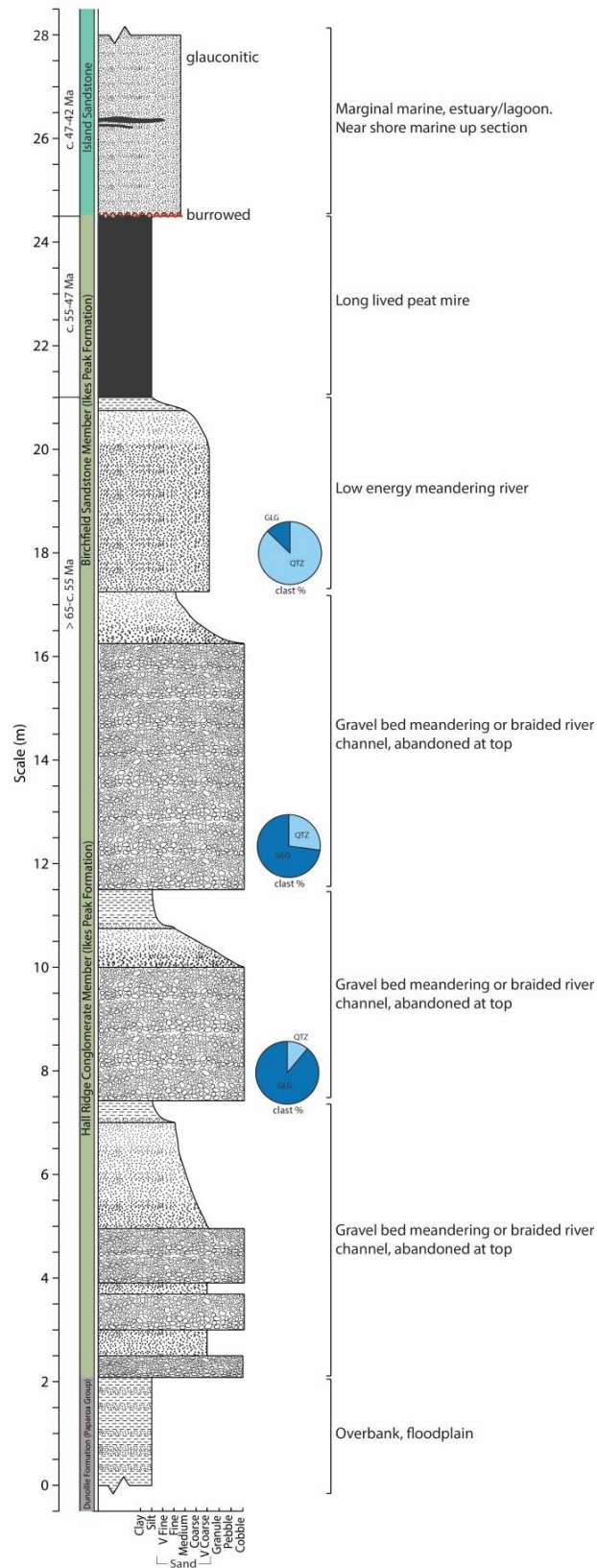


Figure 2.2: Birchfields section showing three fining up meandering river packages. This is the type section for the PBF in the central coalfield.

The section begins in the Upper Dunollie Coal Measures where it consists mainly of thinly bedded sandstones and siltstones with often dirty coals deposited in an overbank floodplain setting (REF). The Dunollie is truncated by a thick conglomerate sequence. The base of this conglomerate shows up to 1.5m of undulation in places and clearly erodes into the Dunollie below but no leaching or weathering is recognized.

The conglomerate is generally clast supported and moderately sorted with cobbles predominating over pebbles. Imbrication is poor but inconsistently indicates a southward palaeoflow. Within the lower 3m of conglomerate there are interbedded coarse-very coarse sandstone lenses which in places are cut by the overlying conglomerates. A 2m section of coarse-very coarse sandstone grading normally into a slightly carbonaceous siltstone overlies the lower conglomerate sequence representing full channel abandonment. Up section a pair of thick conglomerates (2.5 and 5m) with corresponding fining upward coarse- fine sandstones at the top are present. These conglomerates have similar characteristics to the lowermost conglomerate sequence (moderately sorted and imbricated, clast supported, cobble-pebble clasts predominating) but showed variation in clast composition and also show some weakly preserved lateral accretion surfaces.

I initially thought that the lower conglomerate dominating half of the section represented channel conglomerates of a gravel bed braided river. During later interpretation though, there are three apparent fining up sections of cobble conglomerate to silty fine sandstone, each roughly 4-5m thick. Potentially the conglomerate section could be indicative of a sinuous gravel bed meandering river (Reading, 1996; Miall, 2010), with the finer grained sediments representing period of channel abandonment or low flow. While some lateral accretion surfaces and potential longitudinal bar forms are poorly preserved, it is uncertain whether meandering or braiding occurred, possibly somewhere in between as characteristics of both end member types are observed.

Clast counting in the three conglomerate packages confirms an up section increase in quartz content noted by previous authors (Gage, 1952; Newman, 1985; Nunweek, 2001). The two lowest conglomerates contain approximately 15% quartz clasts with the remainder being mainly Greenland Group metasandstones and metasiltsstones (figure 2.2). The lowest conglomerate also contains rare (<0.5%), moderately well indurated, yellow-grey quartzofeldspathic sandstone clasts. These appear to be derived from a different source and are very much a minority amongst the Greenland Group metasedimentary and vein quartz clasts

that predominate. Gage (1952) noted similar clasts within the conglomerate, including clasts of Paparoa Coals. The upper conglomerate and the normally graded coarse sandstone above are much more quartzose (25-30% near the base) and even within the unit there is a notable increase in quartz content up section. The very top of the sandstone layer reaches up to 75-80% quartz.

The upward increase in quartz content is a major compositional trend that has been noted by several previous authors (Morgan, 1911; Suggate, 1950; Gage, 1952; Nathan, 1978; Newman, 1985). This is a reflection of the sediment source becoming more quartzose. As others have inferred before, this is attributed to decreasing supply of recently eroded immature material and instead becoming dominated by a majority of quartzose weathered residuum (Suggate, 1950). Quartz enrichment can be enhanced in either a tropical climate (Martini & Chesworth, 1992) or under acidic peat bogs (Nelson, 1989). The rare quartzofeldspathic sandstone and coal clasts are inferred to be sourced from the lower Paparoa Group (Gage, 1952) thus uplift and erosion of these units must have been occurring somewhere. Under the proposed nomenclature of Nunweek (2001), this conglomerate sequence is classified as the Brunner Conglomerate Member of the Palaeocene Brunner Formation.

Overlying the conglomerate sequence is a 4m section of very coarse sandstone (figure 2.2, 17m). This sandstone is quartzose (80%) and resembles what is typically referred to as 'Brunner Grit'. The sandstone is moderately well sorted, moderately rounded and in some locations shows some minor stratification. The sandstone is dominated on a macro scale by amalgamated lenticular channel forms with rare lateral accretion surfaces parallel to the channel margins. The top of the unit grades into a fine sandstone then carbonaceous siltstone before being capped by a 3.5m thick coal seam. The coal has been identified by Newman (1985) as having a high proportion of degraded maceral content.

The channelized quartzose sandstone is interpreted as a meandering stream with point bar deposits showing meander migration (e.g. Bridge, 2003). The rapid upward fining at the top of the sandstone channels represents abandonment and infilling with floodplain overbank fine sediments culminating in a marshy environment (e.g. Miall, 2010). Nunweek's (2001) classification places the quartzose sandstones and the coal within the Brunner P Member of the Palaeocene Brunner Formation.





Figure 2.3: Contact between the Brunner Conglomerate Member and the Brunner P member is a gully on the west side of hall ridge, down from Birchfields Mine. The outcrop is roughly 4m tall.

The top of the coal is burrowed and overlain by a yellowy calcareous medium sandstone. This surface suggests a time of non-deposition (unconformity) when organisms were able to bioturbate the surface. The sandstone contains a thin, 10cm seam of dirty coal ranging from 1.5m to 2m above the top of the main coal seam but other than this shows no obvious bedding structures. The calcareous nature of the sandstone could indicate a transition to a near shore marine environment but as terrestrial affinities remain (thin coal seam), a near coast lagoonal or tidal marsh setting is probable. The calcareous sandstone is identified as the Island Sandstone based on visual similarities. The transition to a near shore marine environment is inferred to occur a short way up section.

Palynological dating (Raine, 1982; Newman, 1985) carried out on this section reveals that the sandstone and conglomerate is Palaeocene in age (<65-c. 55Ma), hence Nunweek's (2001) proposal for the Palaeocene Brunner Formation. The coal at the top however spans much of the Early Eocene period (c. 55-47 Ma). The burrowed horizon at the top of the coal is identified as an unconformity between the younger Island Sandstone (c. <47 Ma) and the PBF, but the coal itself may also represent a significant proportion of the Early Eocene period as well. The

degraded maceral content of the coals provides evidence for this and Newman (1985) believes the coal may represent an extremely long lived peat mire (c. 8 Ma), likely with multiple periods of accumulation. The unconformity in this location may therefore not be present at all and the c. 8 Ma period could be accommodated entirely within the coal.



Figure 2.4: BCM/Palaeocene Brunner Formation in north bank of the Grey River at the site of the Brunner Mine. The mine adit is directly in the center of the photo but below water level due to high flow on this particular day. The bedding flattens out to the right (east) over the Brunner Anticline and the outcrop in the very far right is about as far down section as is possible. The cliffs above the river are Island Sandstone, the contact with the BCM/PBF occurring just before the stony beach in the far left.

#### 2.4.2. *Brunner Mine, Grey River*

A visit to the site of the Brunner Mine in the south of the coalfield, just outside of Taylorville, encountered a small section of fining up quartzose sandstones just exposed at river level (figure 2.4). These sandstones are mapped as BCM (Nathan, 1978) but are certainly within the eastern center part of the basin, so may in fact be part of the Palaeocene Brunner Formation. No palynology has been attempted on these sandstones or coal so their age is not known. At river level there is a quartzose granule conglomerate with minor pebble clasts which fines up into a quartzose coarse to medium sandstone. Near the top of this sandstone is a 2-3m coal seam into which a mine adit has been driven. It was not examined in detail due to the strong smell of sulfur escaping from the entrance. There is little outcrop beyond this point with bush all the

way down to the river but in the cliffs above, there is the characteristic yellowy, flat bedded calcareous sandstone of the Island Sandstone.

As the type area for the Palaeocene Brunner Formation, the stratigraphy of the central coalfield was then compared to the western and eastern sides of the coal field respectively.

#### *2.4.3. North West Sector*

The stratigraphy of the northwest sector was examined at the mouth of Ten Mile Creek in Ten Mile Bluff (figure 2.5). A good exposure of a massive conglomerate sequence and an upper contact with the overlying Island Sandstone is present here allowing comparisons with the central coalfield.

The conglomerate extends northward along to 12 Mile Beach and is comprised of both Rewanui and Dunollie Formations. The stratigraphy between the Dunollie Formation and the Island Sandstone has been contested since Gage's (1952) original interpretation was made. It was his conclusion that a prominent whitened layer extending approximately 10m down from the contact was conglomerate belonging to the Brunner Formation (older terminology). He attributed the lighter colour of the conglomerate to the significant quartz content that the Brunner Formation displayed elsewhere. The contact with the Dunollie Formation was not discussed in detail by Gage but would be arbitrarily be placed at the base of the lighter conglomerate.

A different interpretation, acknowledged by Gage (1952), was made by Wellman (1950). He suggested that the white layer represented a weathered horizon where the lighter conglomerate was in fact still Dunollie Formation, but had undergone significant in situ leaching with degradation of unstable minerals forming clays. The Brunner Coal Measures were speculated to be a thin (<1m) band existing just above the sharp and obvious unconformity between the leached Dunollie Formation and Island Sandstone.

Not until Nathan (1978) were any further refinements made to Ten Mile Bluff's stratigraphy. In his map of the Greymouth Coalfield, Nathan shows Brunner Coal Measures of Eocene age extending all the way out to the coast. The accompanying booklet notes that the BCM at Ten Mile Bluff are thin (0.3-0.6m) and exists just above the unconformity at the top of the leached Dunollie conglomerate.





Figure 2.5: Ten Mile Bluff. The contact with the Island Sandstone is marked by the sharp transition to scrub at the top of the outcrop. The whitened layer is directly below this contact and the remaining face is conglomerate and sandstone lenses of the Dunollie Formation.

It was obvious that there were irregularities in the interpretation of stratigraphy of Ten Mile Bluff compared to the aforementioned Birchfields Section and in the interpretations of previous authors. Reexamination of the bluff was undertaken to attempt to resolve the controversy (figure 2.6).

The lower part of the section begins from the point where the lower clast count was measured in what is clearly Dunollie Formation conglomerate, approximately 33m down from the contact with the Island Sandstone. Here, a well-rounded, grey-brown cobble conglomerate dominates with clasts generally ranging from 2cm to 10cm and rare 30-40cm clasts. This conglomerate of the Dunollie Formation (Nathan, 1978; Ward, 1996) extends for a significant thickness (estimated 70m+) beyond the base of the section and approximately 33m upwards from the position of the clast count. Imbrication within the conglomerate is poor but indicates a palaeoflow direction to the southeast. Intermittently this conglomerate is interbedded with coarse to very coarse sandstone beds, each around 1m in thickness. Thin section analysis of the matrix component of the conglomerate revealed a dominant quartzose nature with rare feldspar, muscovite and biotite. The feldspars often showed some amount of alteration with rims of clay common.

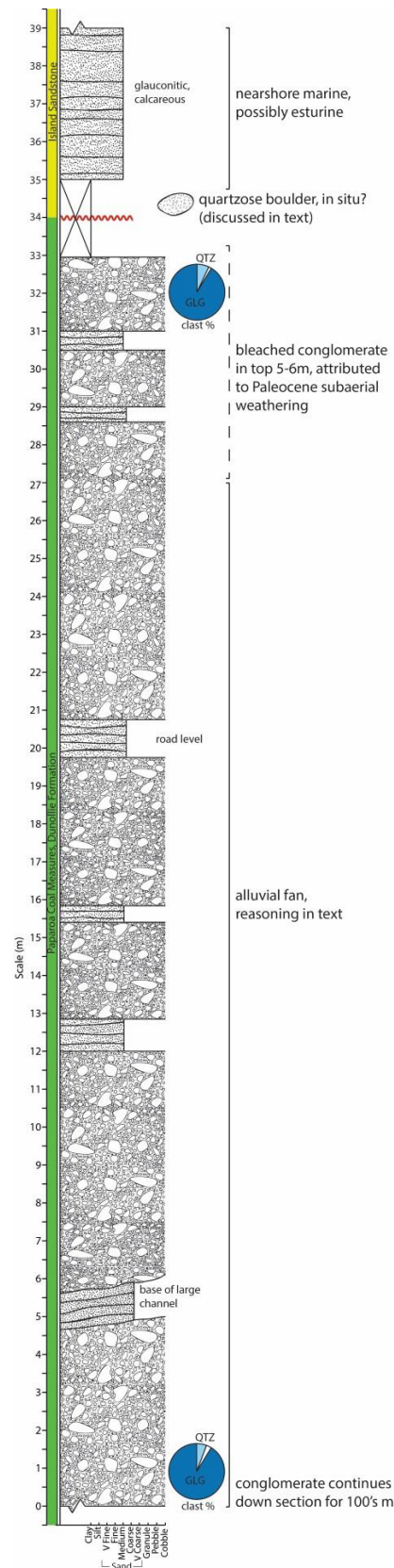


Figure 2.6: Ten Mile Bluff section illustrating the different stratigraphy in the northwest of the coalfield, no BCM or PBF are present and Dunollie Formation conglomerate is directly overlain by the Island Sandstone.

The uppermost 6-7m section of conglomerate is significantly whitened in comparison to the rest of the underlying Dunollie Formation. However, clast size is consistent across the contact to the whitened layer and there is no noticeable difference between the whitened and non-whitened conglomerates, aside from the gradual transition in colour over maybe 2m. Clast composition also shows no noticeable difference between the lower Dunollie conglomerate and the whitened conglomerate. Both contain clasts overwhelmingly dominated by Greenland Group derived metasandstones and metasiltsstones with minor vein quartz and granitic clasts thus they are derived from the same source.

The entire conglomerate section is interpreted as successive braid channels of an alluvial fan (Gage, 1952; Newman, 1985). The poor preservation of AB-plane imbrication (e.g. Nichols & Fisher, 2007) may suggest that bedload transport was minimal and deposition was likely during flood events. The interbedded coarse sandstone lenses reflect periods of lower flow between flood events or edges to the primary flow where finer grained sediments were able to accumulate in channel remnants (e.g. Reading, 1996).

The contact with the overlying Island Sandstone Formation was observed amongst a thick layer of scrub in a gully directly below the prominent face of the bluff (figure 2.5). The top of the conglomerate section was measured in this gully including the upper clast count just below an obvious contact. The top most outcrop below this contact was a clast supported pebble to small cobble conglomerate showing very distinct whitening of the matrix component, but clast composition is identical to the lower Dunollie Formation. Thin section analysis of the matrix showed little difference in comparison to the lower count location but the rare feldspars identified are considerably more altered, often only represented as a grain of clay.

The contact is an unconformity that is gently undulating with up to 1.5m of relief in places. The outcrop directly above the unconformity is poorly exposed in all areas around the bluff. With the exception of one debatably in-situ 60cm quartzose granule-pebble conglomerate boulder on the unconformity in the gully (Figure ... 34m), there are no quartzose sandstones present. Instead a calcareous yellowy brown medium sandstone with some sparse flat bedding is found directly above the unconformity. Outcrop of this unit along the road, approximately 5-8m stratigraphically above the unconformity, contains scattered shell fragments and echinoderm fossils. Thin section analyses also confirmed the presence of rare glauconitic

minerals within the mostly quartzose sandstone. This unit is unmistakably the near shore marine Island Sandstone.

The upper portion of the section is interpreted following what Wellman (1950) and Nathan (1978) established previously. The upper whitened conglomerate has been significantly altered and is inferred to be the result of leaching from the surface during sustained subaerial weathering (e.g. Martini & Chesworth, 1992). Compositionally the entire conglomerate section is identical, thus the upper leached conglomerate is still interpreted to be part of the Dunollie Formation. The unconformity is interpreted to represent the subaerial weathered surface with little erosion post formation.

In contrast to Wellman (1950) and Nathan (1978), there is no substantial evidence for the Brunner Coal Measures present above the unconformity. Nathan's (1978) statement that 0.3-0.6 m of the BCM occur directly above the unconformity is dubious given the unconformity itself is undulating up to twice that thickness. The near shore marine Island Sandstone is instead inferred to rest directly on the unconformity. Any quartzose coarse sandstones or conglomerates present that Nathan (1978) may have identified could potentially be reworked wave base deposits, not necessarily terrestrial BCM and actually belong within the Island Sandstone.

#### *2.4.4. East of the Coalfield*

The measured section in Smoke-Ho creek to the north of Blackball was described to emphasize the very different stratigraphy to the east of the Roa – Mt. Buckley fault zone. This area is termed the eastern flank due to the lack of Paparoa Group strata present here (Gage, 1952; Nathan, 1978). Instead, Eocene (Bortonian) age Brunner Coal Measures (Couper, 1960) sit directly on top of Ordovician Greenland Group basement (Nathan, 1978). This is in contrast to the aforementioned central basin and northwest sector where the earliest Eocene strata is the marine Island Sandstone (Bortonian stage) (Raine, 1982).

Finding a suitable outcrop to describe and measure was difficult due to the dense vegetation at the low altitude around the town of Blackball, and the lack of road cuts or other suitable clearings. A moderately well exposed section along the beginning of the Croesus Track, before Smoke-Ho Creek, was eventually measured as the type section for the greater Blackball area and is illustrated in figure 2.7.

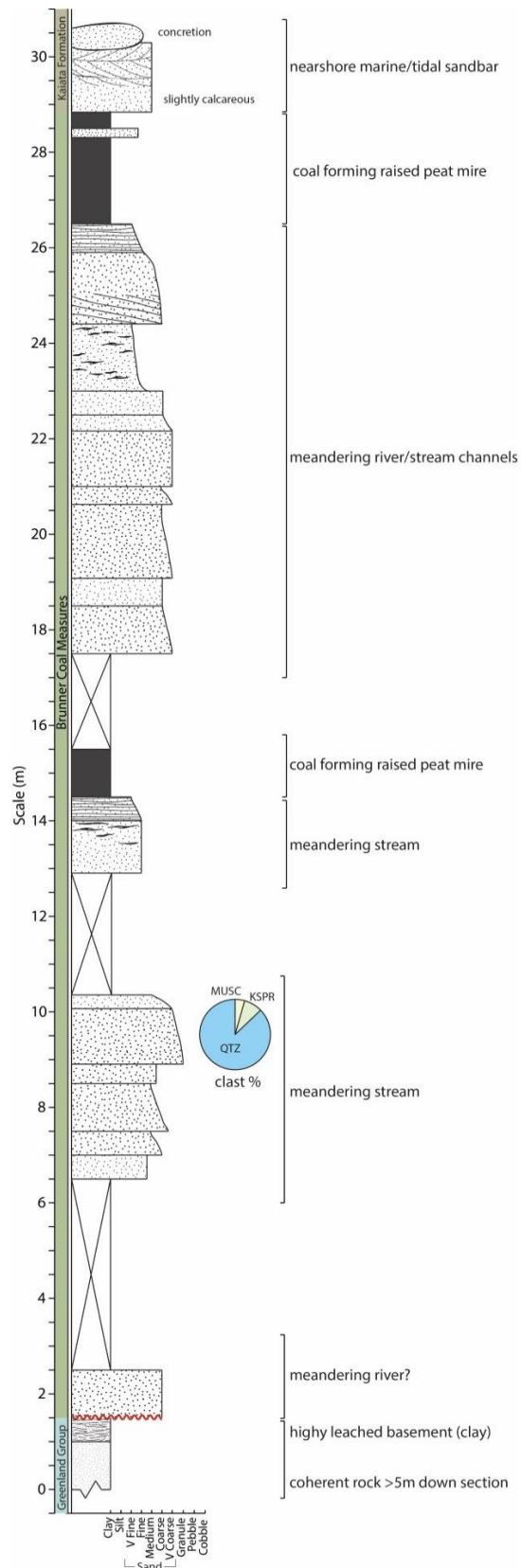


Figure 2.7: Smoke-Ho Creek section showing the typical stratigraphy to the east of the coalfield of meandering river sandstones and coals of the BCM, probably transitioning into the Island Sandstone at the top of the section.



The Greenland Group basement below the unconformity is deeply leached. At least 5m below the unconformity the rock is significantly weathered, enough so that a hammer blow produces a dull thud. At one meter below the unconformity the Greenland Group has been altered to a soft grey clay, weak enough to be broken by hand. The significant leaching of basement is attributed to prolonged subaerial exposure and weathering, the very top clay horizon representing total decay of the parent rock (e.g. Mack et al. 1993).

Directly above the unconformity is 1m+ of grey brown, moderately well sorted, quartzose coarse sandstone with generally sub-angular grains. Beyond this for 4m nothing is exposed but for another 4m above, a near identical unit is seen, though with variations in grain size and some normal grading apparent. These units do not exhibit any structures other than bedding and slight normal grading. A further 2.5m is not exposed before there is a continuation of coarse sandstones for 1m. The top 50cm of this unit contains abundant organic debris and is followed by a 50cm section of carbonaceous laminated fine sandstone.

A sharp but conformable transition to coal indicates the formation of a peat mire. The coal is poorly exposed for up to three meters and detail of the roof of the seam was not clearly seen. It is overlain by a quartzose coarse sandstone akin to the strata below the seam which continues up section with some sparse bedding and grain size variation for 8.5m. Near the top of this interval there is a 1m fine sandstone bed with numerous coaly stringers and some well exposed point bar lateral accretions structures. Up section, a fining up and carbonaceous laminated fine sandstone is succeeded by a 2.5m seam of coal with one 30cm coarse sandstone lens near the top and silty coal above.

The top of the section ends with a yellowy, slightly calcareous, trough cross bedded medium sandstone with crossbed orientations ranging from NW to SE, and is capped by a concretion which overprints the cross beds. At this stratigraphic level the beds tend to dip directly downslope to the southwest and moving up section is no longer possible.

The entire section below the top coal seam is interpreted to be part of a meandering river system (e.g. Bridge, 2003). Lateral accretion surfaces within the sandstone channels are attributed to point bar formation, an indicative feature of a meandering river (Reading, 1996). Intermittent periods of low flow or floodplain deposition resulted in the formation of the finer grained carbonaceous lithologies, including the coals. Coaly fragments included within the sandstones are also an indication of lower flows, potentially reflecting ponding of the river channel in an oxbow lake (Miall, 2010).

The occurrence of coal is interpreted to represent the accumulation of peat. In the lower, poorly exposed coal seam there is a high proportion of silt in the coal suggesting that it was often flooded by proximal streams. The upper coal appears clean with no obvious detrital component thus it is interpreted to have formed in a raised peat mire, free from fluvial interaction (e.g. Esterle & Ferm, 1994). The thin coarse sandstone lens near the top of the upper coal seam (figure 2.7, 28.5m) could be the deposit of a flood event near the end of the mire's accumulation with the overlying silty coal indicating the lower prominence of a less raised or partially collapsed mire.

The prominent trough cross bedding in the calcareous sandstone at the top of the section near the top likely formed within shallow waters with a strong unidirectional tidal or current influence (e.g. Plint, 2010), with sinuous migrating dunes forming the trough cross bedding. This unit is interpreted to be the near shore marine Island Sandstone and represents the end of terrestrial sedimentation.

#### *2.4.5. BCM in the Roa – Mt Buckley Fault Zone*

Slightly further west of Blackball (2km) on the very edge of the Greymouth Coalfield, there are a few instances of Brunner Coal Measures resting unconformably on the Morgan Formation of the Paparoa Group (Nathan, 1978). As the Greymouth Map does not differentiate between the Palaeocene Brunner Formation (Nunweek, 2001) and Eocene age BCM there is some discrepancy in the interpretation of these occurrences. A brief inspection of one of these BCM caps on Paparoa Road (Roa Mine access road) confirmed its occurrence. Only 10-15m of quartzose moderately well sorted, pebbly very coarse sandstone was found sitting very poorly exposed above the Morgan Formation conglomerate. There is no distinction between whether this belongs to the BCM or the Brunner P Member. There is however no quartzose conglomerate at the base, so an equivalent of the Brunner Conglomerate Member is not interpreted to be present here. For this reason it is likely that these outcrops are Mid Eocene (Bortonian) BCM as in all other cases the Brunner P Member is underlain by the Brunner Conglomerate Member.

Regardless of which quartzose unit is present (BCM or Brunner P Member), these occurrences seem only to occur within the Roa – Mt Buckley Fault zone. To the east the Brunner Coal Measures rest directly on Greenland Group Basement and to the west, the Palaeocene Brunner Formation is deposited above the Dunollie Formation. It seems that in the Roa – Mt Buckley

Fault Zone the Waioimo, Rewanui, Goldlight and Dunollie Formations have been removed prior to deposition of the BCM, or, potentially they never existed here. Either scenario suggests that the eastern side of the basin, especially within the Roa – Mt Buckley Fault Zone, has had a more complicated younger history in comparison to the remainder of the basin to the west. This complex history is later elaborated on in the following regional interpretation.

## **2.5. Supporting data from previous work**

In addition to the three main areas examined in the coalfield there were several other important locations that were used as supporting material. These locations are ones that were not visited as part of field work and are therefore the work of previous authors. Several of them have been reinterpreted.

### *2.5.1. Sewell Peak*

A section at Sewell Peak from Newman's (1985) thesis details very similar stratigraphy to that seen at Birchfields (figure 2.8). Like Birchfields, this section has been palynologically dated (Raine, 1982) and supplements our knowledge of the stratigraphy of the central coalfield.

The section begins in the upper Dunollie Member consisting of an alternating sandstone and siltstone sequence (Newman, 1985). A thick conglomerate overlies the alternating beds with an erosional base and continues up section for approximately 16m. The base of the conglomerate is comprised predominantly of greywacke clasts derived from the Greenland Group with some minor quartz enriched horizons. Throughout this unit there is an upwards transition into a quartz clast-enriched conglomerate with some quartzose grit interbeds.

This is followed conformably by a 14m section of commonly cross bedded, normally graded quartzose sandstones in three distinct equally spaced units (Newman, 1985). The top of the lower two units contains a thin (<1m) section of silty mudstone before being truncated by the overlying unit. The uppermost quartzose sandstone unit ends abruptly at a burrowed and highly silicified horizon.

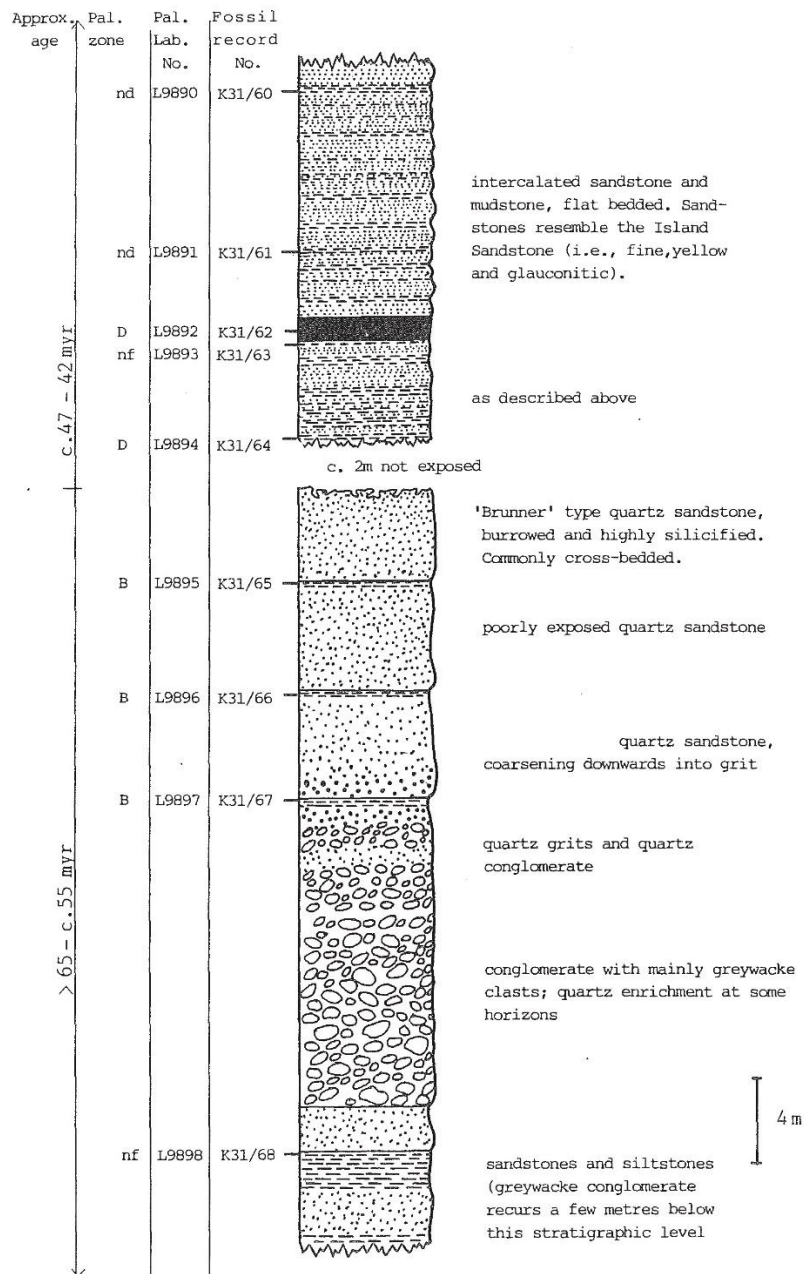


Figure 2.8: Sewell Peak Section from Newman (1985).

Approximately 2m of the section is not exposed beyond this point and the next unit recognized is an intercalated fine, yellow, glauconitic sandstone and mudstone said to resemble the Island Sandstone. It is noted by Newman (1985) though that this unit is generally regarded as BCM due to the inclusion of coal.

Newman (1985) did not include any interpretation of sedimentary features in the section so the following is my own interpretation based on the stratigraphy in figure 2.8. The Dunollie

Formation at the base of the section is interpreted as overbank floodplain deposits as part of a meandering river system. The thick section of conglomerate which overlies represents a period of coarse bed load transport and deposition as part of a high energy probably braided river system (e.g. Nichols & Fisher, 2007). The erosional base of these conglomerates suggests that some amount of down cutting into the Dunollie Formation occurred prior to deposition. The quartz increase up section in the conglomerate is inferred to represent the gradual maturing of the sediment source. The quartzose sandstones above the conglomerate appear to have affinities of a meandering river (e.g. Miall, 2010) and are interpreted to represent a decrease in energy and/or a sediment input. Deposition probably ceased after the upper cross bedded sandstones were deposited and the silicified horizon likely formed as a result of leaching in a soil (e.g. Kraus, 1999). The Island Sandstone at the top of the section due to the inclusion of coal must represent a marginal marine or near coastal environment, possibly an upper estuary or coastal lagoon, due to the marine affinities.

Palynological dating of this section (Raine, 1982) revealed that all the quartzose sandstones and conglomerates beneath the unconformity are Palaeocene in age (<65-c. 55Ma). Samples from the Island Sandstone above the silicified horizon are Middle Eocene (c. 47-42 Ma) in age and the intervening Early Eocene period (c. 55-47 Ma) is lost, represented only by the silicified horizon. This has been interpreted as an unconformity (Newman, 1985).

Based on these ages the sections stratigraphy can be reinterpreted to conform to Nunweir's (2001) proposal for the Palaeocene Brunner Formation. All of the conglomerate can be classified as the Brunner Conglomerate Member and would be approximately 16m thick. The upper quartzose sandstones would be the Brunner P Member and are approximately 14m thick. The unconformity represents a significant time gap, approximately 10 Ma, and Middle Eocene (Porangan-Bortonian) Island Sandstone/transitional BCM rests unconformably above. No true Eocene age terrestrial Brunner Coal Measures are present in the section.

#### 2.5.2. *No Town Bore*

In the south east of the Greymouth Region and somewhat removed from the Greymouth Coal Field is the Notown No. 1 borehole. An oil prospecting well drilled in the summer of 1944, it provides a remote data point for use in later palaeogeographic reconstructions. Basement was intersected at 6,942' (2115m) and was a leached greywacke and argillite. No information on the extent of leaching is mentioned. Unconformably above is 27' (8m) of brecciated

greywacke and argillite which Gage (1952) interpreted as a correlative of the Jay Coal Measure Member. This breccia is unconformably overlain by 43' (13m) of sandstone and coal which Gage (1952) classified as the Brunner Formation. With no age data though, potentially this unit could be either Eocene BCM or the Palaeocene Brunner Formation. This unit is directly overlain by muddy Oligocene limestones of the Nile Group. No calcareous mudstone of the Kaiata Formation is present.

### 2.5.3. *Pike River Coalfield*

Another area important for palaeogeographic reconstructions is the Pike River Coalfield approximately 15km NNE of the Greymouth Coalfield. Here, a similar succession of PCM to those in the Greymouth Coalfield are present and a thin layer of quartzose sandstones (BCM) overlie with apparent conformity. Newman's (1985) PhD thesis contains arguably the best palaeogeographic interpretations for the PCM – BCM transition and attempts to correlate the stratigraphy of Pike River with the Greymouth Coalfield to the south. It was her interpretation that the Pike River and Greymouth PCM were formed in the same south southwest draining basin and that members of the Greymouth stratigraphy had equivalents at Pike River.

The age of the stratigraphy in the Pike River Coalfield is not as well documented as in the Greymouth Basin. Of particular interest is the approximate age range of the Brunner Coal Measures at Pike River. Newman (1985) includes a small set of palynological dates which suggest the BCM there are Middle Eocene (Bortonian-Kaiatan stage). This is similar to the age of the BCM elsewhere, but the equivalent in the Greymouth Coalfield for this time is the Island Sandstone. A direct correlative of the Palaeocene Brunner Formation from the Greymouth Coalfield does not exist at Pike River. This suggests that the Paleocene and early Eocene depositional histories of the two coalfields were different.

The probability of the Greymouth Coal Field extending northward to Pike River is further suggested by cathodoluminescence data of Bassett et al. (2006), reinterpreted here. Detrital quartz grains in the eastern compositional suite of the PCM were found to be predominantly of a metamorphic origin. This suggests that they are derived from the metamorphosed lower crustal rocks from within the Paparoa Core Complex to the north. Bassett and her colleagues concluded from this that the Greymouth Basin must have moved past the core complex with sinistral transcurrent movement during the Late Cretaceous, being supplied directly by sediment from the erosion of an eastern highland. Unfortunately large scale (100km) sinistral

offset of the Greymouth Basin is not supported by the regional basement geology (Nathan, 2002). There is no evidence that significant strike slip motion has occurred in the vicinity of the Paparoa Core Complex since its formation. Therefore the conclusions of Bassett et al. (2006) are not justified but the derivation of the metamorphic quartz from the Paparoa Core Complex to the north of Pike River suggests continuity between Pike River and Greymouth Basins.

## **2.6. Nomenclature revision**

It was noted by Nunweek (2001) that the naming of the stratigraphic subdivisions within the Paleocene Brunner Formation could be revised; presumably to avoid the continued use of the term 'Brunner'. He also notes that the Palaeocene Brunner Formation itself could be renamed more appropriately. With consideration of current usage and relevance to the location of the type section (Birchfields Opencast), two name changes to the formation nomenclature are proposed in addition to renaming of the formation itself. The Paleocene Brunner Formation is here renamed the Ikes Peak Formation after the prominent cliffs formed by the unit in that region. The Brunner Conglomerate Member is renamed the Hall Ridge Conglomerate Member after the good exposure of the member along much of Hall Ridge. The Brunner P Member is now referred to as the Birchfield Sandstone Member after the type locality where it was first defined. These names avoid the term 'Brunner' and indicate the type location of the members by using geographically relevant names.

The location of the contacts between the Formations and members is also redefined. The base of the Ikes Peak Formation and the Hall Ridge Conglomerate Member is now defined simply as the contact at the base of the conglomeratic facies. This differs from the classifications proposed by Ward (1997) and followed by Nunweek (2001) for the rest of the PCM, in that the last carbonaceous horizon is irrelevant in the division of units. It is my interpretation that the base of the conglomerates represents a far more important boundary and is therefore more appropriate for the basal contact of a unit.

The boundary between the Birchfield Sandstone and Hall Ridge Conglomerate is gradational but is defined as the transition from conglomerate (including clast sizes from pebble upwards) into finer granule conglomerates and sandstones. Although this is an arbitrary division, the contact is now mappable despite being gradational. Quartz content is not considered to be

appropriate for use as a divisor as composition is related solely to provenance, not lithology type and is more difficult to determine in the field.

No changes are proposed to the upper contact of the Ikes Peak Formation and Birchfield Sandstone Member. It was felt this has been defined appropriately by previous workers and the contact with the Island Sandstone is still used. The division of Birchfield Sandstone from Middle Eocene (Bortonian) BCM around the mouth of Nine Mile Stream and other coastal exposures (Couper, 1960) may be resolved by the presence of an or unconformity (potentially silicified) like what is present at Sewell Peak.

The extent of the Ikes Peak Formation is mostly similar to the BCM in Nathan's (1978b) map of the coalfield, but only occurring above the rest of Paparoa Group. The division between the Ikes Peak Formation and the BCM can be made by the presence of the Hall Ridge Conglomerate Member. The Hall Ridge Conglomerate is found across most of the coalfield. It is thickest on Hall Ridge, Ikes Peak and between Mt Davy and Sewell Peak, being absent any further east of Mt Davy. To the west the Hall Ridge Conglomerate extends out to the coast but in the northwest it is absent in the vicinity of Ten Mile Bluff. Northwards, all outcrop is lost and to south the formation is mostly concealed below the Rapahoe Group. The BCM at the Brunner Mine on the Grey River may actually be the most southerly outcrop of the Ikes Peak Formation as the base of the section here begins to look characteristically like the Hall Ridge Conglomerate.

The Birchfield Sandstone specifically follows a mostly similar trend to the above, with the exception of costal exposures. Middle Eocene (Bortonian) Brunner Coal Measures are instead present above the Hall Ridge Conglomerate (Couper, 1960; Nunweek, 2001) in the very west of the coalfield. It was shown by Nunweek that the Birchfield Sandstone occupied a slightly smaller area than the underlying Hall Ridge Conglomerate.

Thickness variations across the coalfield suggest a gradual thickening of the Ikes Peak Formation towards the east. This is primarily based on thinner occurrences in outcrops toward the coast (Nunweek, 2001) and the absence of the formation in the northwest at Ten Mile Bluff (Figure 2.3). In the northwest the alluvial fan conglomerates of the Dunollie Formation (Gage, 1952; Newman, 1985) may have been elevated with respect to the center of the basin which would explain why deposition did not occur there. In the east the formation is thickest at Sewell Peak and less than 1km further east is absent. This transition coincides approximately with the modern day Roa – Mt Buckley Fault Zone.



The proposition of Ikes Peak Formation as a part of the Paparoa Group as opposed to a Palaeocene age member of the Brunner Coal Measures is justified by the extent of the formation. In no instance do either the Birchfield Sandstone or Hall Ridge Conglomerate Members extend beyond the known extent of the Paparoa Group, and hence the confines of the Greymouth Basin. If the Ikes Peak Formation was an older member of the BCM then a diachronous transition with gradual migration out of the basin would be expected. In the east of the coalfield, across the Roa – Mt Buckley Fault Zone and into the Mid Eocene (Bortonian) BCM at Blackball no such transition occurs. Also in the coastal exposures in the West of the coalfield BCM sits unconformable on the Hall Ridge Conglomerate Member (Nunweek, 2001) which does not suggest a diachronous contact between the Ikes Peak Formation and the BCM. The Ikes Peak Formation is therefore retained as the upper most formation of the Paparoa Group and not part of the Brunner Coal Measures.

## **2.7. Regional Interpretation**

It is clear that the Greymouth Coalfield has experienced a varied geological history in comparison to the rest of the study area. With sedimentary deposition dating back to the middle Cretaceous, the area is stratigraphically complex, more so than other locations. Equally complex is the differing theories for the basin and the strata within, especially with respect to the Brunner Coal Measures and the proposed Ikes Peak Formation. Attempting to resolve issues around these two units and producing a unified model for the basin during the Late Palaeocene – Early Eocene was the aim of investigations in the Greymouth area.

### *2.7.1. Tectono-Sedimentary Model of the Greymouth Basin*

The current widely accepted model for the Greymouth Basin is that of Ward (1997) with faulting to the east throughout deposition of the Paparoa Group. This however has been recently revised by Cody (2015) who suggests dominant faulting to the west of the basin for much of the Paparoa Group. Her revision was based on the sedimentology of the lacustrine formations which showed no evidence of uplift and therefore faulting to the east, instead being truncated by the younger Roa – Mt Buckley Fault Zone. This interpretation reverts to Gage's (1952) original interpretation of major faulting and uplift to the northwest for the Greymouth Basin and truncation of the Paparoa Group by the Roa – Mt Buckley Fault Zone after deposition. This

new model however does not adequately explain the presence of the Ikes Peak Formation, in particular the geometry and extent discussed in the previous section. Therefore, a tectono-sedimentary model detailing the period of the Ikes Peak Formation was constructed (figure 2.9). This model does not extend back into the early Palaeocene or Cretaceous or explain the rest of the Paparoa Group in detail but is based on and conforms to Cody's (2015) revised western dominant basin bounding fault.

#### *2.7.2. Top Dunollie Formation*

The upper Dunollie Formation can be separated into two distinct facies groups. In the northwest at Twelve Mile Beach and inland for approximately 1-2km (Gage, 1952) the formation is characterized by the conglomerates shown in figure 2.5. These conglomerates are interpreted to belong to an alluvial fan (Newman, 1985) draining from a high to the northwest. Although not well exposed in outcrop, these conglomerates are inferred to interfinger and transition eastward into the interbedded sandstones and siltstones that typify the Dunollie Formation through the rest of the coalfield. These are generally regarded as meandering river channel and overbank floodplain facies (Gage, 1952; Nathan, 1978b) but in the center west of the coalfield on Hall Ridge resemble a more deltaic environment, assumedly near the edge of the Goldlight Formation lake or an equivalent.

Like the other Paparoa Group formations, the Dunollie is truncated on the eastern side by the Roa – Mt Buckley Fault Zone. Meandering stream facies are inferred to have likely extended further east during the Early-Middle Palaeocene based on Cody's (2015) isopach models, thus there is no indication of faulting on the east during this time. The conglomerates to the northwest and the inferred high from which they are sourced is instead interpreted as the location of a major basin fault (Gage, 1952; Cody, 2015). This is shown by the conglomerate thickness to the WNW in figure 2.9.

#### *2.7.3. Hall Ridge Conglomerate Member*

In the Middle Palaeocene (Raine, 1982) the basin saw deposition of the Hall Ridge Conglomerate. Although an erosional contact with the Dunollie Formation exists it does not represent a significant time gap (Raine, 1982; Newman, 1985) and deposition was likely continuous. The conglomerate is interpreted as a coarse bedload gravelly braided or

meandering river and based on the similarities in stratigraphy across the central coalfield, occupied much of the basin. Gradual thinning and onlap of the Hall Ridge Conglomerate onto the Dunollie in the west (Nunweek, 2001) suggests that this side of the basin was a low gradient slope heading towards an inferred high further west. In the northwest at Ten Mile Bluff the member is completely absent. The alluvial fan that formed the Dunollie Formation conglomerates is inferred to have been elevated with respect to the center of the coalfield hence the Hall Ridge Conglomerate was not deposited here. The abrupt loss of the conglomerate east of Mt Davy/Sewell Peak, where it is thickest (14m), is attributed a major topographic high in the east, approximately correlating with the present day Roa Mt Buckley Fault Zone. Variation to the north and south of the coalfield is not known.

From these observations it seems that the Hall Ridge Conglomerate Member was not influenced by the same fault(s) that controlled deposition of the lower Paparoa Group strata. The gradual thinning toward the bounding fault of the Dunollie Formation (western fault) does not suggest that it was active during deposition (e.g. Einsele, 2000). The inferred low gradient slope in this direction could be either due to relict topography from Dunollie time or rotation and tilting of the basin floor to the east. Rotation and tilting is favored because the inferred prominent high in the east and abrupt loss of the Hall Ridge Conglomerate Member beyond, is interpreted as an eastern basin bounding fault. This fault is inferred to have been initiated in the mid-Late Palaeocene and the associated uplift, erosion and transport of coarse clastic sediment into the basin is reflected by the deposition of the Hall Ridge Conglomerate.

Faulting on the eastern flank is further suggested by the composition of the Hall Ridge Conglomerate. In clast counts near Birchfields Mine, rare moderately indurated, yellow-grey quartzofeldspathic sandstone clasts inferred to be derived from a different source to the remainder of the composition may indicate erosion of Paparoa Group strata at this time. These peculiarities were also noted by Gage (1952) in two instances of the Brunner Formation (now classified as Ikes Peak Formation). He mentions the inclusion of clasts of the characteristic Morgan Volcanic Conglomerate and clasts of Paparoa Coal within the Ikes Peak Formation south of Roa and near Rapahoe. Gage (1952) also believed that the inclusion of Morgan Volcanic Conglomerate and Paparoa Coal within the Ikes Peak Formation was indicative of uplift and erosion of the lower Paparoa Group.

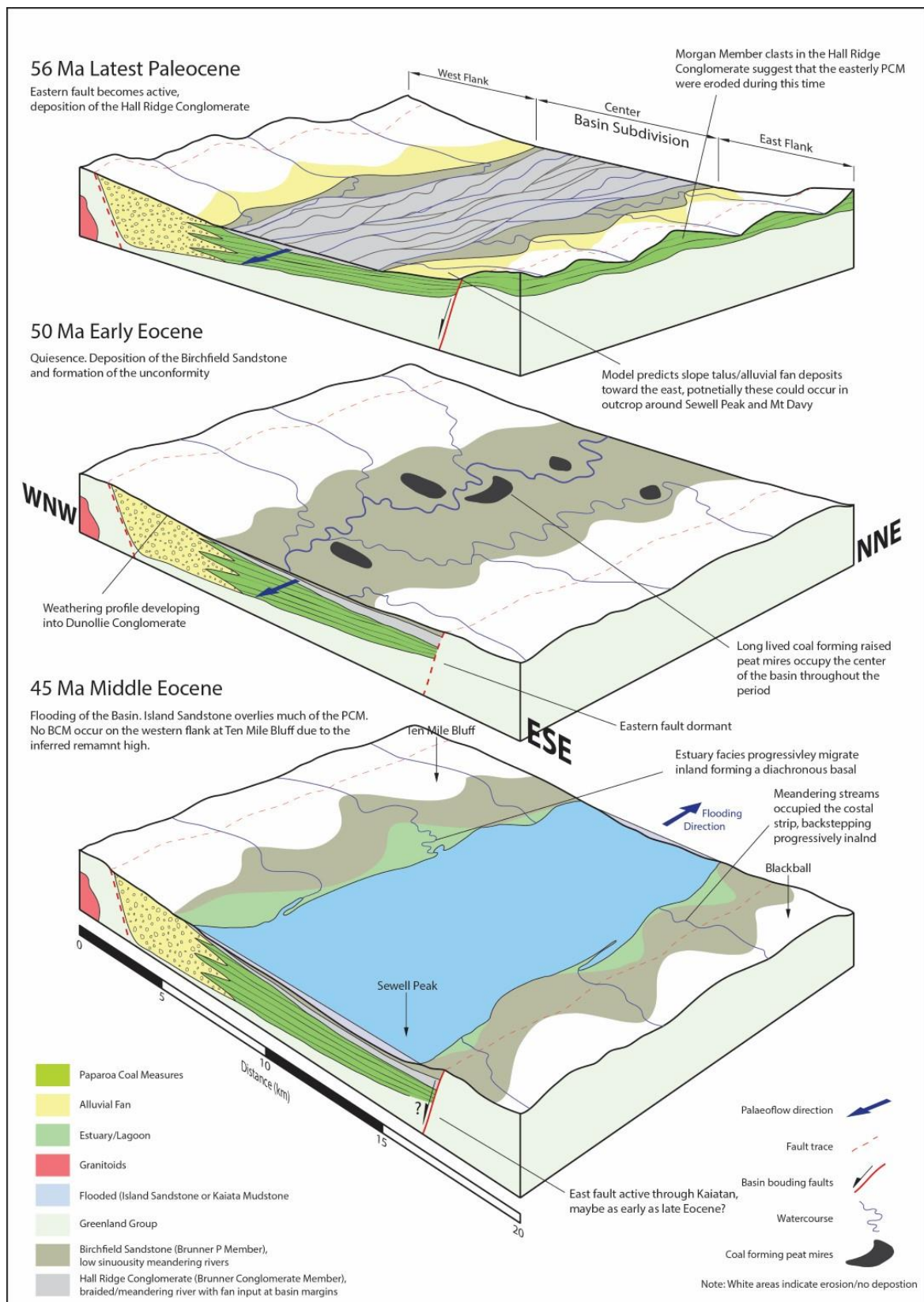


Figure 2.9: Tectono-sedimentary model of the Greymouth Basin. A schematic representation of the inferred depositional and tectonic history from the end of the Ikes Peak Formation up until deposition of the Island Sandstone and Brunner Coal Measures.

An eastern fault initiated at this time resolves many issues with the current basin models. The lack of upper Paparoa Group formations east of the Roa – Mt Buckley Fault Zone and BCM sitting directly above the Morgan Formation can be explained by an eastern fault uplifting the eastern side of the basin. Uplift and erosion in the east also provides the sedimentary source for the Hall Ridge Conglomerate. Suggate (2015) has also come to a similar conclusion of faulting initiated in the east prior to deposition of the BCM and after the Paparoa Group to explain the lack of upper Paparoa Formations east of the Roa – Mt Buckley Fault Zone. My interpretation however has been made including the stratigraphy present within the coalfield as opposed to solely the absence of strata in the east.

Rounding in the Hall Ridge Conglomerate though does not support direct input of sediment from the east. Generally the clasts are moderately to well-rounded and inferred to have been transported for some distance prior to deposition. While sedimentary breccias and angular alluvial fan conglomerates may exist proximal to the inferred eastern fault scarp (e.g. Busby & Perez, 2012), the majority of the Hall Ridge Conglomerate is interpreted to have been sourced from further north and transported south. The source is still inferred to be associated with uplift of the eastern side of the basin though due to the timing and inclusion of Paparoa Group clasts within the conglomerate.

#### *2.7.4. Birchfield Sandstone Member and Unconformity*

The Hall Ridge Conglomerate Member grades up section into the Birchfield Sandstone Member. The Birchfield Sandstone is interpreted as a continuation of fluvial deposition in the form of sandy meandering rivers, overbank floodplain facies and coal forming peat mires. This is attributed to decreasing energy and/or reduction in sediment supply rate. The landscape is inferred to have less topography than that during deposition of the Hall Ridge Conglomerate with any uplifted areas mostly eroded. Steep relief was not present and the rate of sediment supply was likely diminishing, hence the reduction in grain size. The Birchfield Sandstone covers almost the same extent as the Hall Ridge Conglomerate with the exception of not extending as far to the west, thinning out somewhere not far (1-1.5km) west of Hall Ridge. Like the conglomerate, the Birchfield Sandstone ends abruptly against the Roa – Mt Buckley Fault Zone. The deposition of the Birchfield Sandstone is also accompanied by a dramatic increase in quartz content, often reaching over 80% of the total composition.

The Birchfield Sandstone is interpreted to represent the cessation of faulting in the basin all together. The reduction in grain size and the increase in sediment input from beyond the basin margins suggests both cessation of faulting and transition to a landscape of lower relief (e.g. Busby & Perez, 2012). The quartzose nature of the sediment source is attributed to sub aerial chemical weathering of the surrounding landscape and production of a quartz rich residuum (Suggate, 1950). However, the extent of the Birchfield Sandstone is still controlled by the remnant fault controlled basin shape. In the east the fault scarp, while probably reduced to a low gradient slope, limited deposition any further east. In the west, the maximum extent of the Birchfield Sandstone being less than the Hall Ridge Conglomerate is attributed to more rotation and tilting of the basin floor and the western side experiencing some minor uplift. This limited the extent of the Birchfield Sandstone to the west.

At the very top of the Birchfield Sandstone there is a prominent c. 8 Ma unconformity surface. Outside of the basin this is recognized as BCM resting unconformably on Greenland Group basement. Within the basin the unconformity is typically at the top of the Birchfield Sandstone with near shore marine Island Sandstone or lagoonal-estuarine BCM above. In the center of the coalfield the unconformity is absent and instead the c. 8 Ma period is accommodated by the coal seam (Brunner Seam) at the top of the Ikes Peak Formation.

As others have concluded before (Nathan, 1978; Newman, 1985), it is interpreted here that the Greymouth Coalfield acted as a shallow basin in the landscape over this period of unconformity. Local deposition, while probably ceasing at times, was mostly continuous in the very center of the basin indicated by the long lived coal forming peat mires. Toward the edge of the basin and beyond in the surrounding landscape, this unconformity developed a deep leached horizon representing extensive subaerial chemical weathering of the surface (Elias & Mock, 2013).

#### *2.7.5. Middle Eocene Island Sandstone and Brunner Coal Measures*

Wide spread deposition in the basin did not again occur until the Middle Eocene (Porangan-Bortonian). Following the formation of the unconformity and long lived coal forming peat mires of the Birchfield Sandstone a transition to marine sedimentation and deposition of the Island Sandstone occurred. This transgression was gradual as coal in the lower most Island Sandstone suggests that a marginal marine environment, either estuarine or lagoonal was present. This is however only seen in the central coalfield. In coastal exposures to the west,

Middle Eocene (Bortonian) Brunner Coal Measures overlie the Hall Ridge Conglomerate (Couper 1960; Nunweek, 2001). In exposures to the east in the Roa – Mt Buckley Fault Zone BCM directly overlie Morgan Formation and further east around Blackball they lie unconformably on Greenland Group basement (see figure 2.7, Smoke-ho Creek). In the northwest at Ten Mile Bluff the Island Sandstone rests directly on the leached Dunollie Formation conglomerate and no BCM are present.

It seems that the Island Sandstone and the marine transgression it represents was localized to the central axis of the Greymouth Basin. There is no evidence for fault control at this time so it is interpreted that deposition was confined by the inherited topography of the landscape only. Away from the center of the basin toward and on the uplifted flanks, the Island Sandstone is inferred to transition into the terrestrial Brunner Coal Measures. In the northwest at Ten Mile Bluff Island Sandstone rests unconformably on the Dunollie Formation despite being in the far west of the basin. This is attributed to the inferred higher elevation of the alluvial fan mentioned in the previous section and also probable wave cutting during deposition (e.g. Landis et al., 2008).

Deposition of the Island Sandstone and Brunner Coal Measures is interpreted as an indication of the onset of widespread regional subsidence. This is especially true with deposition occurring beyond the confines of the Greymouth Basin across much of Westland (Suggate, 1950; Nathan, 1986). A question mark is placed on the recommencement of faulting in the basin then, as the eastern fault (or an equivalent) is a major tectonic feature known to be active during the following Late Eocene (Kaiatan stage) (Nathan, 1978; Suggate, 2014).

## **2.8. Conclusions**

The Greymouth Region is characteristically fault controlled for much of its history. This is true not only for the Paparoa Group but also for the Mid-Late Palaeocene Ikes Peak Formation. The revised Ikes Peak Formation (formerly Palaeocene Brunner Formation) indicates that at the end of the Palaeocene the basin experienced a switch in the basin bounding fault from west to east. This was followed by a quiescent period in which deposition was localized to the center of the basin while elsewhere sub aerial weathering and development of an unconformity proceeded. The onset of regional subsidence is marked by deposition of the near shore marine Island Sandstone in the basin and coarse quartzose Brunner Coal Measures across the rest of the landscape.

## **Chapter 3 The Buller Region**

### **A fault controlled landscape**

#### **3.1. Introduction**

The most northern part of the study area, the Buller Region, covers most of coastal North Westland and contains the thickest occurrence of the Brunner Coal Measures in the study area. The region loosely fits the area collectively called the Papahaua Range, extending from the Buller River in the south to the Mokihinui River in the north and bordered to the west by the Tasman Sea. The Papahaua Range is a distinctive feature in the modern landscape and represents the inverted remnant of a large fault bounded basin (herein referred to as the Buller Basin). This basin forms the northern part of the Paparoa Trough (Norgate et al., 1997), a western segment of the larger Challenger Rift System that was actively subsiding in the Late Eocene and Oligocene (Kamp, 1986; Furlong & Kamp, 2013).

Significant quantities of high grade coking coal occur throughout the Buller Region along the Papahaua Range and extensive mining has been ongoing for over 140 years (Morgan & Bartrum, 1915). The earliest of these mines were small scale and produced coals mostly for local use. As larger co-operative ventures emerged mining became more prolific and around the turn of the century, with the input of the government, coal mining began on a large scale (Morgan & Bartrum, 1915). Currently only one major mine (Stockton-Webb Opencast) is operating, with two smaller scale mines (Rockies and Cascade) also working at the time of writing.

The presence of mining has meant a considerable amount of exploration and research has already been undertaken with several reports and papers of interest to this research currently published. The first major investigation was performed by Morgan & Bartrum (1915) in their geological survey of the Buller-Mokihinui Subdivision. While now well outdated, this work laid the foundations on which all subsequent studies were based. Nathans (1996) *Geology of the Buller Coal Field* produced the most detailed geological map of the region to date. This map became the primary method used for identifying potential outcrop of the unconformity and BCM. In the south of the region the *Geology of the Buller-Lyell Map* also by Nathan (1978a), was used as the Buller Coalfield map did not cover this area. The more recent *Greymouth and Nelson Qmap Bulletins* (Nathan et al., 2002; Ratternbury et al., 1998 respectively) are also useful in providing a general overview of the Buller area.



The Papahaua Range is the northern extension of the Paparoa Range across the Buller River (figure 1.1). The Kongahu Fault Zone at the western edge of the Papahaua Range is a reactivated normal fault that controlled deposition in the Buller Basin from the Late Eocene and through the Oligocene (Kamp et al., 1996). The Kongahu Fault Zone does not currently truncate the overlying Cenozoic sequence and instead has formed a monocline. The west limb of this monocline dips steeply toward the sea disappearing beneath Quaternary terraces on the coastal plain near Waimangaroa (Nathan, 1996). Although poorly exposed, this west limb contains a near complete section of the Cenozoic sequence. The east limb forms the nearly horizontally bedded Denniston and Stockton Plateaus (Nathan, 1996; Kamp et al, 1996), with the resistant Brunner Coal Measures generally all that remains of the Cenozoic succession.

The most recent characterization of the Brunner Coal Measures in the Buller region from a sedimentological perspective was by Flores & Sykes (1996). While their focus was on coal distribution and quality, much of their research was based on characterizing depositional settings, facies distributions and overall evolution of the BCM. The scope of their research covered much of the same area of this study, so as reference material this paper was invaluable.

Basement consists of either Greenland Group sandstone and argillite, hyalodacite and microgranodiorite of the Berlins Porphyry, or other intrusive rocks of the Rahu Suite (Nathan, 1996). In all cases basement is altered and leached to some degree. Generally, the upper portions of the basement directly below the unconformity have been altered to clay. The majority of unstable minerals have deteriorated and quartz fragments are often all that remains of the original rock. In the very far south of the coalfield there are some limited occurrences of mid Cretaceous Pororari Group Hawks Crag Breccia unconformably overlying these basement rocks. These angular sandstone breccias formed in fault bounded half graben basins related to formation of the Paparoa Metamorphic Core Complex (Ring et al., 2014).

Above the leached basement and rare Pororari Group are minor and intermittent localized basal conglomeratic facies. These are the earliest deposits recognized within the Brunner Coal Measures. The localized conglomerates (generally less than 10m thick) suggest deposition within the confines of valleys prior to the widespread deposition of the overlying quartzose sandstones (Flores & Sykes, 1996). It is inferred that these basal conglomerates represent stream incision prior to deposition of the rest of the BCM.

Immediately above the conglomerates, although generally resting directly on basement are the characteristic silicified quartzose coarse sandstones the BCM are known for. Within these

sandstones are commonly interbedded fine sandstones and siltstones, thick coals, minor shaly coal and occasional pebble conglomerate horizons. There is typically one, thick (up to 20m) low ash, high sulfur coal seam (Buller Seam Member) with common splits and horizontal grading into siltstones (Titheridge, 1993). Coarse sandstones, fine sandstones and siltstones above the coal often display cross bedding in varying orientations. The top of the BCM are usually eroded away (present day), but a gradual transition into the Kaiata Formation occurs at the top of the unit in complete sections.

Additionally, Titheridge (1993) has provided strong evidence for syndepositional faulting within the BCM. Using seam splitting in the coals and the relationship to known faults, he concluded that the BCM must have been deposited whilst small scale faulting was active (10-30m).

At the southern end of the Buller Region are the Mt Rochfort and Te Kuha sectors. These two locations are within 5km of each other but differ stratigraphically and are both dissimilar to the rest of the region. At Mt Rochfort a prominent basal conglomerate has been known for some time but has mostly been overlooked (Titheridge, 1993; Flores & Sykes, 1996). Currently the thick conglomerate (up to 270m) (Titheridge, 1993) is included within the Brunner Coal Measures as a localized basal lithofacies. Other than noting its presence though, the only interpretation as to why it occurs was a possible half graben suggested by Titheridge (1993). The stratigraphy of the Te Kuha sector to the south was similarly originally defined as a thick section of BCM sitting atop the mid-Cretaceous Hawks Crag Breccia (Nathan, 1978a). Recent investigations by CRL energy, on behalf of Stevenson Mining, have concluded that the majority of what had been classified as BCM is in fact more likely the equivalent of the Late Cretaceous to Early Paleocene Paparoa Coal Measures found further south (Dutton et al., n.d.). The possibility of older than Eocene age strata in the Buller Region and potentially identifying the existence of a local sub basin prompted further investigation of both areas.

### **3.2. Methodology**

The Buller Region was approached slightly differently than the Greymouth Basin. Previous work here had detailed much of the stratigraphy and there were no obvious issues (nomenclature or otherwise) that warranted any further work. Instead the region was divided into the Northern and Southern Buller Basin and looked at the Brunner Coal Measures and the conglomerate and Paparoa Coal Measures below respectively.

The Northern Buller Basin included a few examples from across the area to outline the general characteristics and depositional history of the BCM in the region. These areas were chosen based on previous work (Nathan, 1996; Flores & Sykes, 1996) and accessibility. As field work ensued however, some new and previously over-looked areas were discovered to contain undocumented stratigraphy important for the tectonic history of the basin. These are presented following the examples of the general stratigraphy.

The Southern Buller Basin focused solely on the stratigraphy below the Brunner Coal Measures. This included the conglomerate at Mt. Rochfort and the Paparoa Coal Measures at Te Kuha.

Both the Northern and Southern Buller Basin included measured sections, clast counting, palaeoflow measurements, some field and aerial mapping around the Mt. Rochfort area, creation of two lithofacies transects and reinterpretation of drill hole data.

### **3.3. Northern Buller Basin**

#### *3.3.1. Key sections*

##### *3.3.1.1. Coalbrookdale-Escarpment*

The Denniston Plateau provides a good general overview of the Buller Regions stratigraphy and the basal unconformity. One section from near old Escarpment Mine and another six sections from the Coalbrookdale area were used to illustrate this. Both areas are situated on the Denniston Plateau with Coalbrookdale more central and Escarpment on the very eastern edge overlooking Cascade Creek and mine. Of the six Coalbrookdale sections one is used as the type section for the area and the others (Appendix 3) are collated into a cross section for identification of palaeotopography relief (figure 3.4).

##### *3.3.1.2. Coalbrookdale*

The Old Mines section at Coalbrookdale was chosen as the type section for the whole Coalbrookdale area (figure 3.2). At the base of the section there is a well-developed leached horizon into the basement Berlins Porphyry. The upper 2m of this profile is completely altered to a clay with residual angular quartz fragments and small flakey muscovite grains (figure 3.1). The deteriorated basement and clay layer are interpreted as the result of extensive chemical

weathering prior to deposition of the BCM. The clay represents the extreme end product of weathering with most of the parent rock altered and only resistant quartz and muscovite remaining.

The unconformity at the top of the clay is knobbly with 10cm deep scoured hollows forming an uneven surface. The undulating surface is inferred to be a reflection of the soil surface at the time of deposition as fluvial erosion capable of scouring out the deep hollows would more likely have removed the layer all together (e.g. Kraus, 1999). Therefore the knobbly surface is likely a remnant feature.

The hollows are infilled with yellowy coarse sandstones that are very quartzose. The coarse sandstones become interbedded with very fine sandstone to siltstone layers up section for 1.5m. The sandstones and interbedded siltstones were poorly exposed but do show fining up relationships. These are interpreted as individual thin channels or sheet flows. Probably the latter as they are thin (0.5m) and are consistent along the outcrop (traced out 70m). They are therefore interpreted as part of the floodplain system, not an active channel.



Figure 3.1: Unconformity and weathered basement at Coalbrookdale. The pack at center right is sitting of the highly weathered clay layer, the unconformity just above. Hyalodacite of the Berlins Porphyry occupies the foreground and lower right of the photo and grades into the weathered horizon.

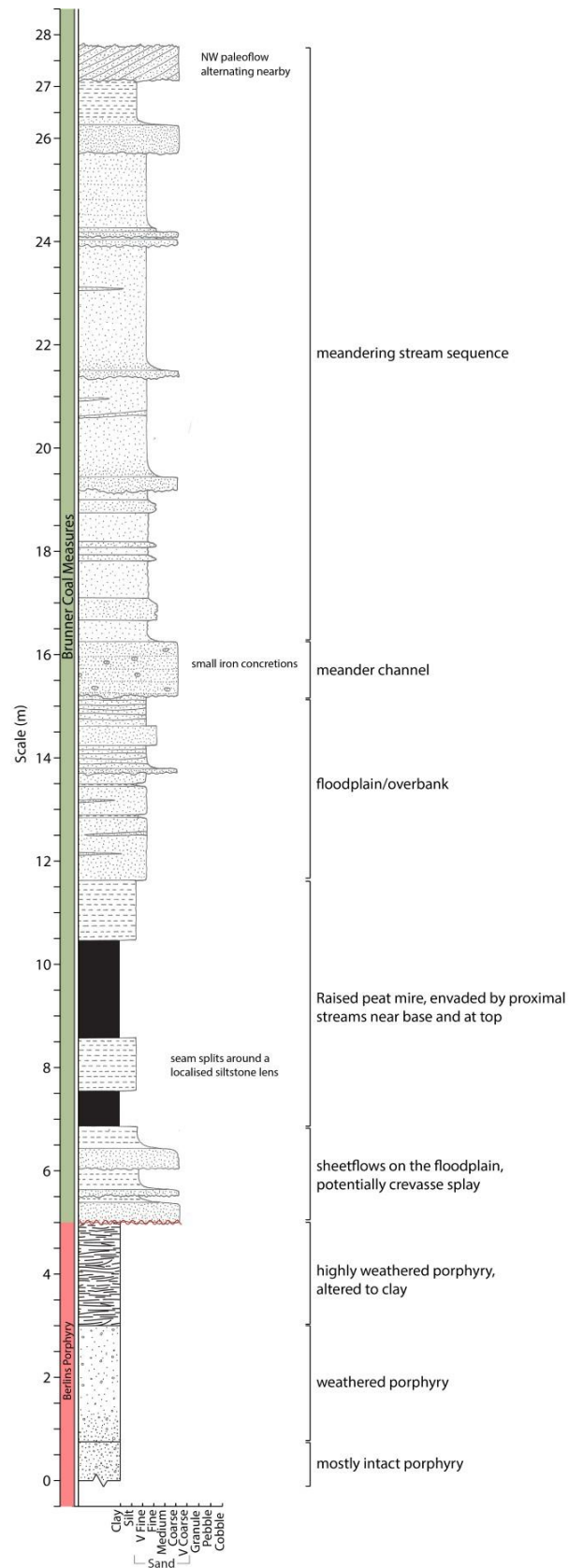


Figure 3.2: Coalbrookdale section, detailing the weathered basement rocks, the meandering stream facies, interbedded coals and the unconformity at the base.

Overlying the sandstones is a thick 4.5m seam of coal (Buller Seam Member (Titheridge, 1993)) which contains two approximately 1m thick carbonaceous siltstone beds which can be seen to pinch out over approximately 50m when traced laterally. The coals and the interbedded carbonaceous siltstones are thick and therefore represent a significant period of time. The siltstones within the coals indicate that the peat mire was occasionally flooded (Esterle & Ferm, 1994) so this particular section was either nearer the edge of the mire, or it was not raised far above the surrounding flood plain.

The coal is truncated by a moderately sorted, light yellow, medium sandstone which continues up section for 2m. Within this bed are scattered fine sandstone lenses and two 10cm siltstone beds. The beds are thin, flat and extend continuously for great distances (at least 40m before not exposed). Truncation by a 20cm very coarse sandstone band gives way to a carbonaceous laminated medium sandstone that extends up for 1.5m. These sandstones are interpreted as channel proximal overbank/floodplain deposits rather than the channel itself because of their great lateral continuity (at least 70m). The very coarse sandstone represents a proximal crevasse splay channel whereas the carbonaceous laminations in the upper medium sandstone bed indicate periodic flows, typical of a floodplain.

The proximal floodplain deposits are truncated by a faintly horizontally bedded, very coarse sandstone with numerous iron concretions that pinches out along the outcrop in a large 30m wide channel (15.5m in Figure 3.2). The basal surface shows some undulation with up to 20cm relief. Overlying this is a series of fining up coarse sandstone to medium sandstone beds (12m), which often show erosional bases and lenticular shapes across the outcrop. In places there may be some very faint shallowly dipping lateral accretion surfaces parallel to the inferred channel axis. There are scattered fine sandstone lenses throughout. The top most bed shows well defined lateral accretion surfaces and not too far away similar stratigraphic units have well preserved cross bedding. This 12m thick stack of lenticular sandstones is interpreted as the main channel in a large meandering river. The basal horizontal bedding suggests deposition along a straight reach initially (Bridge, 2003) followed by deposition in a migrating bend as shown by the lateral accretion deposits.

#### 3.3.1.3. *Escarpment*

Not far from Coalbrookdale, the Escarpment section was measured at the very eastern edge of the Denniston Plateau. The Escarpment section was included to highlight the variation that can be present in the weathering of basement.

Escarpment had no obvious leached horizon in the underlying basement (figure 3.3). Instead, the apparently un-weathered microgranodiorite of the Berlins Porphyry forms the basement of the section here. The unconformity between the porphyry and the BCM above is undulating with up to 1m of relief across the outcrop so an erosional period in which the leached section was removed is likely.

Overlying the unconformity is a very coarse sandstone approximately 0.5m thick with some occasional granule conglomerate lenses. This bed is truncated by a 2m thick granule-pebble conglomerate layer in the base of a 2m coarse sandstone. This sandstone unit has a lenticular shape when traced out extending at least 15m before outcrop is lost. The upper third fines slightly upward into a medium sandstone at the very top and also contains some coaly pieces resembling sticks or branches which are parallel to bedding. These two basal coarse sandstones are interpreted as channel fill due to the lenticular shape and erosional nature at the base. The inclusion of coaly bits in the top of the unit is inferred to represent a decrease in energy.

An abrupt transition to a silty coal which itself grades into a carbonaceous siltstone and then laminated fine sandstone is interpreted as channel abandonment. The varied carbonaceous siltstones, sandstones and silty coal are representative of low energy, interpreted as swamp environment in an abandoned channel depression.

Another two sections of fining upward coarse to fine sandstone are present above, both with an erosional base and lenticular shape like the channels below. The repetition of channels that fine upward is interpreted as a migrating meandering river deposit with each fining up sequence culminating in channel abandonment (e.g. Reading, 1996).

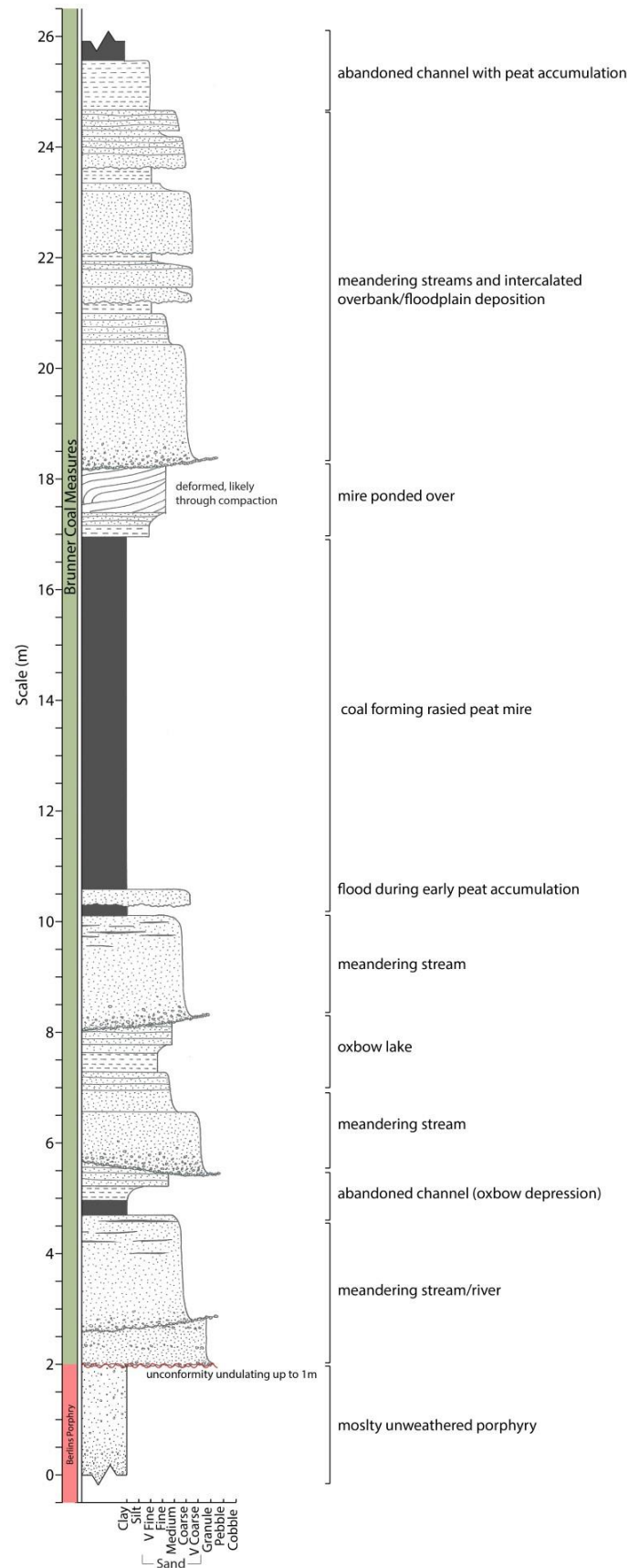


Figure 3.3: Escarpment Section, showing the lack of weathering of basement but otherwise similar meandering stream and interbedded coal facies like in the Coalbrookdale section.



The fining upward sandstones are overlain by a 7m thick coal seam which, aside from a 30 cm coarse sandstone band at the base, is continuous. The coal appears mostly to be clean but a thin horizon near the base is silty. The top 0.5 m grades back to silty coal to siltstone to fine sandstone. The transition to coal is interpreted as another abandonment of the channels below, yet on this occasion a significant raised peat mire was established and likely resisted flooding from proximal streams or rivers. The clean nature of the coal indicates the lack of fluvial processes affecting the peat formation. The transition back to siltstone and fine sandstone at the top suggests flooding of the mire by lateral streams or small lakes.

The coal grades into a carbonaceous fine- medium sandstone at the top which is visibly deformed. The deformation in these units is interpreted as post-depositional differential compaction instead of slumping or sliding during sedimentation as the coal is similarly deformed.

The top of the section was only exposed in an inaccessible cliff so the following is based on appearance alone. The coal at the top was the next point where close inspection was possible. Above the deformed fine sandstone another normally graded very coarse sandstone to siltstone unit is present. The base of this layer contains a thin granule conglomerate as in the lower channel sequences and is interpreted as a return to active fluvial sedimentation with migration and down cutting of a channel into the fine sandstones below. The top of the unit contains a series of laterally continuous intercalated siltstones, fine sandstones and medium- coarse sandstones. These are inferred to represent the abandonment of the channel and transition to alternating sandstones and siltstones indicative of proximal floodplain. The upper medium sandstones have abundant carbonaceous laminations and the top 1m of siltstone is very carbonaceous before grading into a silty 0.5m seam of coal. This seam of coal at the top of the section was chosen as an ideal stopping point due to the flat dip then encountered on the plateau's surface and the difficulty of accurately measuring thicknesses in that situation. As an estimate, 10-20m of usually cross bedded, coarse-medium sandstones and interbedded often carbonaceous siltstones occurs beyond the top of this coal. These are interpreted as a return to a stacked meandering channel sequence with no other thick coals occurring.

#### *3.3.1.4. Summary of Escarpment and Coalbrookdale Sections*

The stratigraphy and interpreted depositional history of Escarpment and Coalbrookdale sections closely matches the work of previous authors on the BCM of the Buller Coalfield

(Titheridge, 1993; Flores & Sykes, 1996; Nathan, 1996). The sections are predominantly comprised of quartzose coarse sandstones and interbedded fine sandstones, siltstones and coals, interpreted as meandering river and associated floodplain facies. Deposition occurred during a period of slow subsidence in which thick coals were able to form. Marine transgression followed, initially with notable low gradient coastal plain preceding estuarine or marine facies, and later with deposition of the fully marine near shore Kaiata Formation (Flores & Sykes, 1996). This sequence is regarded as the generalized history of deposition for the BCM.

In both the Escarpment section and at Coalbrookdale, outcrop ended before the upper transition into marine facies. An attempt to find a suitable detailed outcrop where the entire section from basement to Kaiata Formation is exposed was unsuccessful. The best effort was to measure an approximate thickness of the BCM along the Iron Bridge road in the Upper Waimangaroa catchment. The thickness obtained was approximately 47m which is comparable to the thickness of the BCM in the Buller Coalfield given by previous authors (Titheridge, 1993; Flores & Sykes, 1996).

#### *3.3.1.5. Coalbrookdale Transect*

To complement the above depositional history a more detailed look at the basement unconformity was accomplished with a palaeotopographic transect made from the collation of sections in the Coalbrookdale area (Figure 3.4) (Appendix 3). The unconformity clearly shows how the landscape at the time of initial deposition included significant relief, enough so that the overlying stratigraphy is affected to a large degree. This topography indicates a high to the west and a valley in the middle of the transect. To the northeast there is a gradual rise which is interpreted as a low gradient surface.

At the basal contact, the leached weathered soil horizons extending down into the basement show varying thickness depending on the location along the transect. It seems that depth to which the leaching has penetrated into basement is greater within the valley, which is also beneath the thickest coal. Potentially this could be either reflecting a less well developed weathering profile on the high to the west, or that the leaching below the coal is further deteriorating basement post depositionally, or a combination of both.

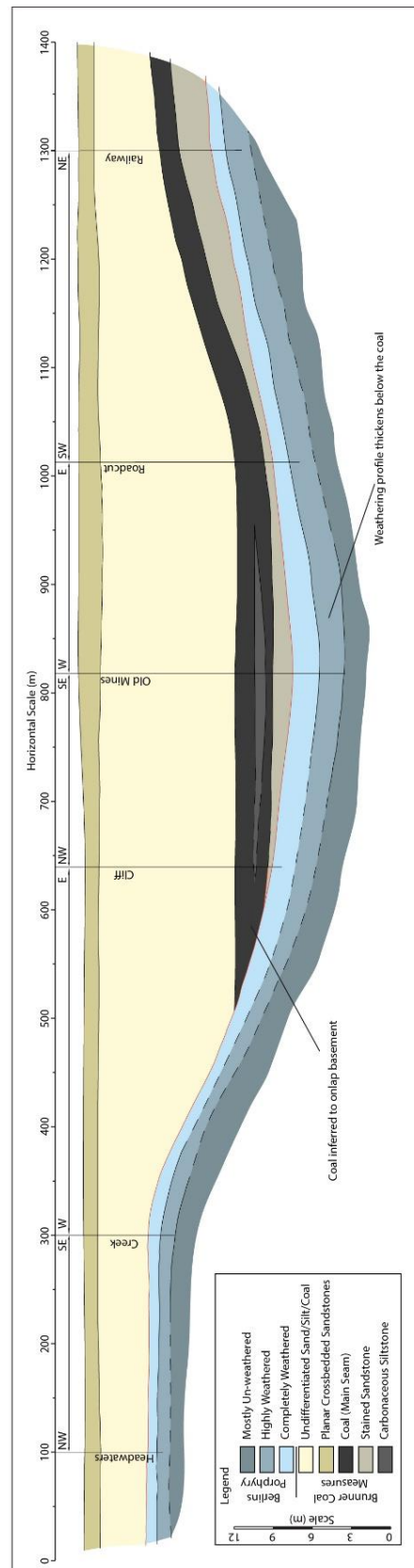


Figure 3.4: Coalbrookdale palaeotopographic transect. Influence of preexisting topography on deposition of the BCM is clear in this cross section with the coal and much of the overlying sandstone inferred to onlap onto the basement unconformity.

In the strata overlying the basement unconformity, only the coal and a prominent cross bedded sandstone could be traced between outcrops. The sandstone was used as the datum from which all the sections were correlated as it generally continued without interruption and was high in the stratigraphy allowing better interpretation of the coal's geometry.

The coal sits on average about 1-3m above the unconformity (Figure 3.4). Any sandstones present below are visibly darkened on the surface due to coating with coal dust. When a fresh face of these sandstones is encountered they often appear more discolored (reds and oranges) than the equivalent sandstones above the coal. The coal itself is of mostly consistent thickness, although within the center of the valley there is a noted siltstone lens within. Importantly the coal onlaps or pinches out against the high to the west whereas toward the east it is continuous.

The peat mire that the coal represents may have been deposited diachronously and migrated to the northeast as the valley filled with sediment. Likewise, the coal may represent one part of a fanning dip sequence in a small half graben against an up faulted block forming the western high. A potential syndepositional fault could be indicated by the high inferred here following the work of Titheridge (1993). Either scenario may be the case though.

#### *3.3.1.6. Chasm Stream*

The Chasm Stream outcrop, the most northerly outcrop of the Brunner Formation to be included within this thesis, is an actual outcrop example of syndepositional faulting. The area is lower than the rest of the Papahaua Range and as such is highly vegetated restricting the availability of outcrop. No section was found adequate to be measured but fortunately a small road cut on Charming Creek Road was discovered to contain the basement unconformity and a small syn-depositional fault.

Illustrated in Figure 3.5 & 3.6, the outcrop is dominated by a small half graben structure (5m from fault to hinge). Basement here is a highly weathered granite with the majority of unstable minerals altered to clays and angular quartz grains scattered throughout the clay groundmass. Directly above the granite is an approximately 3m thick coal seam that grades into a carbonaceous siltstone/very fine sandstone at the top of the outcrop. At the very base of the hanging wall block is a barely exposed, colluvial deposit with interspersed coal fragments. Within the coal of the hanging wall are two well indurated bands which allow bedding orientation to be identified and a silty very fine sandstone wedge adjacent to the fault. Bedding

shows a distinct fanning geometry, with the coal thickening toward the fault (approximately 1.5m from what can be seen).

The half graben is interpreted to be a syndepositional feature, primarily due to bedding in the immediately overlying coals fanning toward the fault, and converging toward the hinge. The interfingering wedge of silty very fine sandstone directly adjacent to the fault also appears to be fault controlled. The half graben's dimensions are no more than 5m from fault to hinge and from what can be observed, the fault has upwards of 1.5m of offset. The orientation of the fault trends roughly 240°. The remainder of the coal seam and very fine carbonaceous sandstone above the hanging wall coal show no evidence of offset by the fault.

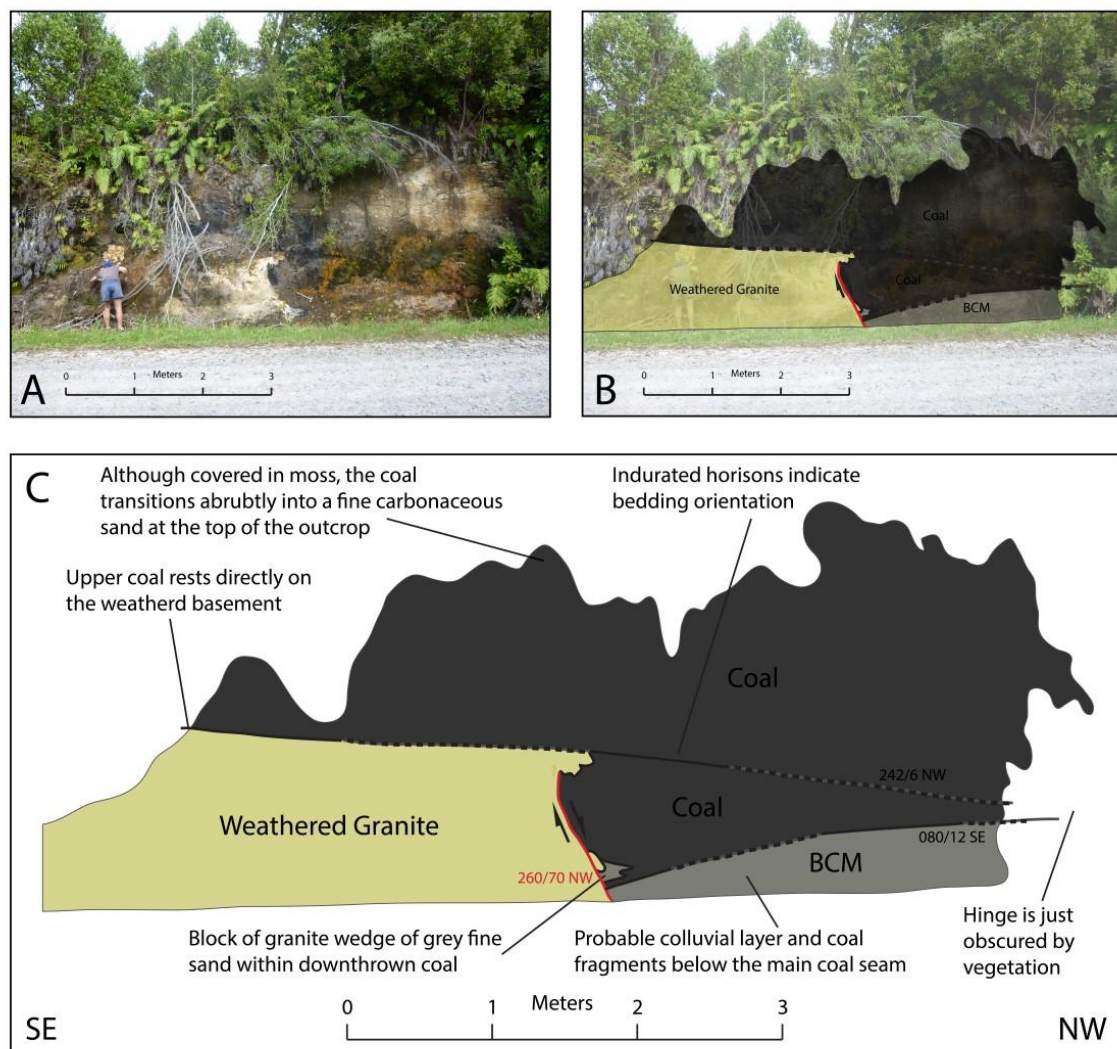


Figure 3.5: Chasm Stream syndepositional half graben at the very northern end of the Papahaua Basin (2km SE of Seddonville). Small scale syndepositional faulting highlights the size down to which such features can have an effect on the stratigraphy.



Other than the lowest portion of the outcrop, there is no evidence in the overlying sedimentary layers to suggest that faulting continued. This was an important observation which highlights the difficulty of recognizing small scale syndepositional faulting. The outcrop also demonstrates just how small a scale such processes could be occurring on.



Figure 3.6: Detail of the half graben. The thin section of BCM in the lower right contains coaly fragments and appears to be a colluvial deposit below the coal. Also note the protruding weathered granite to the left of the spade handle.

### 3.3.2. Depositional History of the Northern Buller Basin

The Brunner Coal Measures of the Buller Region are what the author would consider the type area for the unit. Sandstones and siltsstones, interspersed thick coals and an always predominantly quartzose composition typify the general stratigraphy of the area. With only a few exceptions, the combined Coalbrookdale and Escarpment sections represent the stratigraphy of the Buller Region.

Like Flores & Sykes (1996), Titheridge (1988; 1992; 1993) and Nathan (1996) previously, it is my interpretation that the BCM are the result of deposition in a low lying basin dominated by fluvial sandy meandering rivers, oxbow lakes and flood plain areas. The basement across the area is generally deeply leached, reflecting a period of prolonged subaerial exposure and

chemical weathering (Suggate, 1950). The quartzose nature of the BCM is attributed to prolonged subaerial weathering removing all other minerals. Degradation of the parent rock in and beyond the basin margins resulted in a quartzose residuum which was then later mobilized and deposited within the basin in a meandering river and floodplain setting.



Figure 3.7: Grand Canyon estuary lithofacies. A large road cut on the Stockton Mine road exposes the upper portion of the BCM just before transition into the Kaiata Formation. The estuarine interpretation is based on the lateral continuity of beds, calcareous nature and occasional point bar formations.

Large, raised peat mires became established near the beginning of deposition and remained for long periods to accumulate the thick coals present today. A gradual marine transgression progressively invading this terrestrial basin caused base levels to rise and the peat mires were eventually flooded by the rivers and overlying estuaries (Flores & Sykes, 1996; e.g. Robinson & McCabe, 1992)(example in figure 3.7). While still resembling the lower meandering river and floodplain facies, variably oriented cross bedding and lateral accretion surfaces in these upper units indicates very sinuous rivers (Miall, 2010). The low gradient required for these rivers is inferred as formation of a flat coastal plain as the marine transgression ensued. The upper contact with the Kaiata Formation and thus the transition to marine deposition is only

seen in a few places but is very gradual. Usually, estuarine and/or deltaic facies are interfingered with shore face deposits making the boundary ultimately difficult to define (Flores & Sykes, 1996). As such it is considered more of a transitional zone and a gradational contact.

The defining feature of the Buller Coalfield, in relation to other occurrences of the BCM, is that here the coals and fluvial sandstones are thick. Discounting the conglomerates at Mt Rochfort the BCM in the Buller Coalfield are anywhere from 30-60+m thick (Titheridge, 1988; Flores & Sykes, 1996). This is significantly more than other areas thus the Buller Basin is inferred to have been a feature present during deposition.

Complementing this interpretation is the occurrence of syn-depositional faulting in the earliest BCM. Titheridge (1993) has documented such processes occurring within the BCM on both the Stockton and Denniston Plateaus through interpretation of seam splitting geometry and proximity to known faults. The Chasm Creek outcrop discovered in this research is the first outcrop evidence for such features and complements Titheridge's conclusions, thus small scale (<50m) syndepositional faulting was prevalent during deposition of the BCM.

### **3.4. Southern Buller Basin**

With the Buller Region's Brunner Coal Measures being well studied previously and the Coalbrookdale, Escarpment and Chasm Stream outcrops only complementing the findings of others work, attention was instead turned to the very south of the Buller Coalfield. Here, a thick basal conglomerate of the Brunner Coal Measures was known to exist but was inadequately described and interpreted. This conglomerate gained attention during the very initial reconnaissance of the area as its occurrence was anomalous in respect to the rest of the Buller Basin. The two locations that were focused on in the area were the Mt Rochfort and Te Kuha sectors (see Figure 3.13, Geology of the southern Buller Coal Field). A collection of sections and drill hole logs were measured and used for interpretation in addition to a field and aerial mapping of the Mt Rochfort area.



### 3.4.1. Key Sections

#### 3.4.1.1. Mt. Rochfort

Mt. Rochfort, situated at the very southern end of the Denniston Plateau, is an iconic landmark of the Westport area due to the TV translator at the summit (figure 3.8). Access was relatively good because of this and the area was visited multiple times during field work. The basal conglomerate for which the area is known is up to 270m thick below the summit (Titheridge, 1993). Investigation of this conglomerate eventually resulted in three stratigraphic columns spaced along the prominent east facing cliffs. The Mt Rochfort Section (Figure 3.9) was chosen as the type section for the conglomerate as it contains the thickest occurrence. The other two sections can be found in Appendix 3.



Figure 3.8: Looking south to Mt. Rochfort. All of the cliff section is composed of conglomerate. The very top of the slope (on average 5-10m) sees the transition to the BCM which extend out across the Denniston Plateau to the northeast (right of the photo).

The thick basal conglomerate in the Mt Rochfort section was measured to be at least 215m thick but the total thickness was not able to be determined. Outcrop was lost in bush cover and not until another 90m below was the Hawks Crag Breccia seen. Instead, the thickness of the conglomerate from Titheridge (1993) of 270m is used as an estimate for this section.

The good outcrop in the cliffs is predominantly composed of a clast supported, poorly imbricated, mostly well sorted, cobble conglomerate. Intermittently within the conglomerates are thin (1-5m) lenses of medium to coarse sandstones to granule conglomerates. These layers delineate the bedding orientations (typically around 150/10-15°) and show that the conglomerates have very slight lenticular shapes as they down cut into the sandstones.

The conglomerate is predominantly composed of Greenland Group derived clasts at the base and becomes slightly more quartzose up section. Only at the top of the conglomerate, just below the transition to the quartzose coarse sandstones of the BCM, does quartz content of the conglomerate approach 50% of the total clast composition. The ultimate quartzose (c. 90%) transition occurs roughly coincidentally with the transition to coarse sandstones (figure 3.10).

The contact to the overlying coarse sandstones is on an abrupt decrease in grainsize as well as the transition to more quartzose composition. This change is gradational though and no obvious erosion is seen to have occurred between the conglomerate and the sandstones. The sandstones are very quartzose, sub rounded to sub angular, moderately sorted and often occur within lenticular channel forms. The coarser sandstones are interbedded with fine sandstones and carbonaceous siltstones as well as one thick coal seam (Buller Seam Member).

The conglomerates may represent either a coarse braided river or an alluvial fan but the lack of good accessible outcrop and imbrication measurements meant the nature of the channel network could not be determined (imbrication suggests a general SW palaeoflow direction). The upwards increase in quartz content suggests that the sedimentary source was becoming slightly more mature as deposition continued. The rapid increase in quartz content and decrease in grainsize at the top suggests sedimentation slowed, the gradient of the slope had likely decreased and a very mature source became dominant.

The comparatively thin cap of traditional Brunner sandstones above the conglomerate is the equivalent to what is seen across the rest of the Denniston Plateau. Predominantly coarse lenticular quartzose sandstone meander channels and fine sandstone/siltstone overbank floodplain deposits with one main thick seam of coal (Buller Seam Member).

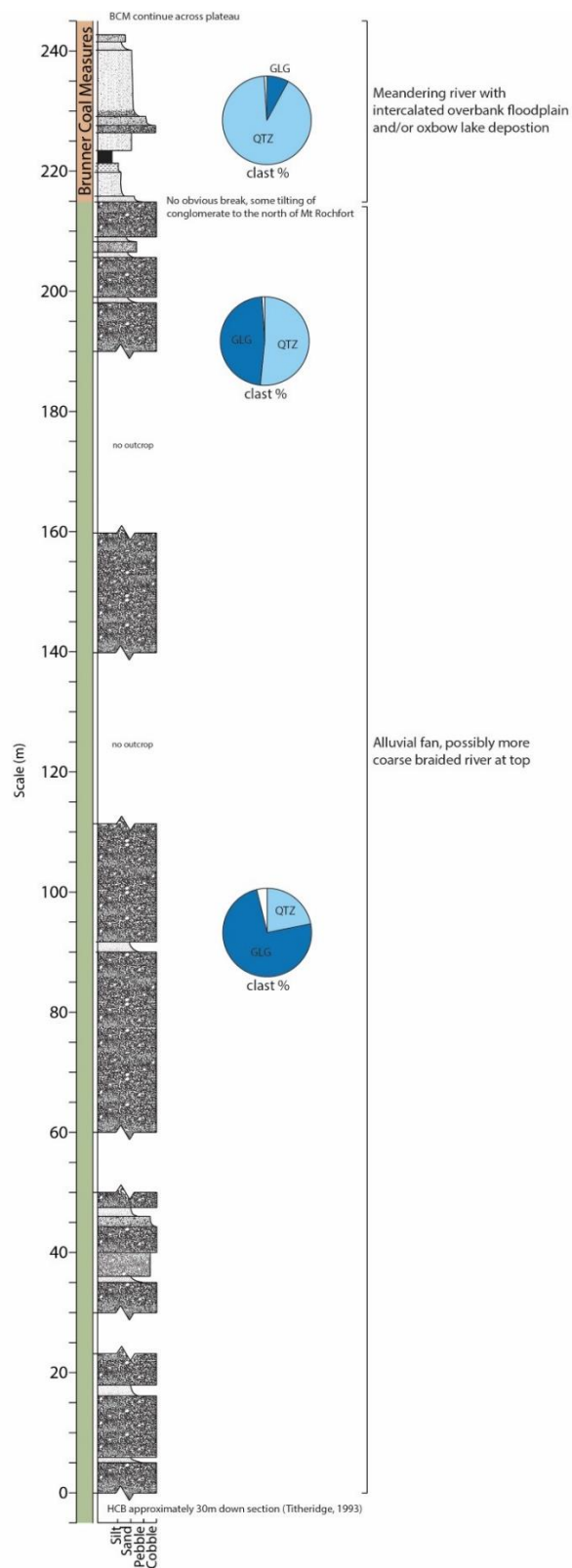


Figure 3.9: Mt Rochfort Section. A thick section of polymict grading to quartzose conglomerate is present below the characteristic quartzose sandstones of the BCM in the upper 25m.



Figure 3.10: The transition from conglomerate to coarse sandstone. The change likely represents an unconformity but not age data is available to support this. Obvious tilting to the SW is seen in the conglomerate as well as erosion/truncation by the upper conglomerate layers.

The thick conglomerate however is something of an anomaly. While local basal conglomeratic lithofacies are seen elsewhere in the Buller Region (Flores & Sykes, 1996) they are typically no thicker than 2-3m. The hundreds of meters of conglomerate in the cliffs of Mt Rochfort is more than just a localized basal conglomerate. Such an occurrence in an inferred mostly low lying landscape with minor small scale faulting seemed unlikely. Further investigation looked southward to the Te Kuha sector to see if similar anomalies would be found there.

In addition to the measured sections, some remapping of the Mt Rochfort area was completed to define the upper and lower contacts of the conglomerate. The top contact was defined as the transition from cobble conglomerates into granule or smaller grain sizes and was completed by field mapping. The lower contact was based on Nathan's (1996) Geology of the Buller Coalfield map and interpretation of aerial photography. These revised contacts are included into the revised map of the Southern Buller Coalfield (Figure 3.13).



#### 3.4.1.2. *Te Kuha*

The Te Kuha sector, despite being so close to Westport, is accessible only by helicopter or on foot and was not visited during field work. Fortunately, CRL energy and Stevenson Mining allowed access to information obtained during previous exploration of the area. This included 25 cored and geophysically logged holes in total, 12 from a previous exploration effort in 1985/86 and 13 new holes completed in 2012.

Te Kuha's stratigraphy has been recently revised as part of the new exploration effort and what had been classified as all Brunner Coal Measures (BCM) is now recognized as both Paparoa Coal Measures (PCM) and BCM (Dutton et al., n.d.). This classification does not currently take into account absolute ages as palynology has not yet been attempted. The classification instead is based on the characteristics of the interbedded coals and comparisons to other Westland coals. The low ash, low sulfur coals in the lower seams of Te Kuha are very similar to the PCM south at Greymouth and Pike River Coalfields, thus are considered time equivalent on that basis (Dutton et al., n.d.).

Four drill hole logs contained the entire section from the BCM, through the PCM like units and down into the Hawks Crag Breccia at the base. Tk-19 contained the thickest occurrence of the PCM like sedimentary rocks and was used as a type log for the Te Kuha Sector (figure 3.11). The core logging was not done as part of this research (logged by Aaron Dutton of CRL energy) but detailed core photos and the original lithologic core log were made available so that interpretations of depositional settings could be made in this thesis. Specific details regarding the coals cannot be discussed due to confidentiality agreements.

The basal 8 meters of the core is composed of angular breccia granite clasts identified as the Hawks Crag Breccia (figure 3.11) (Nathan, 1978a). Above an obscure contact at 155m down from the collar, there are 100m of litharenite sandstones, mudstones, granule conglomerates and some minor coals. These, based primarily on the coal characteristics, have all been reassigned to the PCM (Dutton et al., n.d.). From the core photos primarily, a series of stacked coarse sandstone grading into carbonaceous siltstone packages dominate the section. Each fining up sequence is roughly 2-4m in thickness and occasionally includes polymict granule conglomerates or minor thin coals.

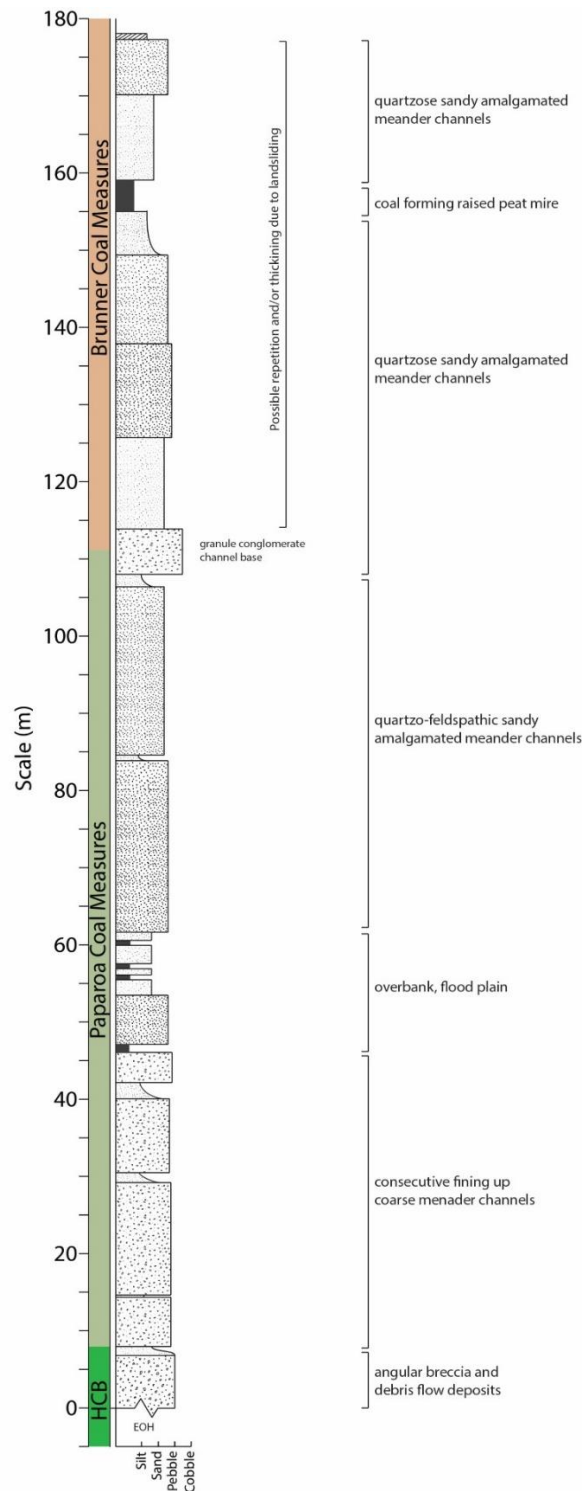


Figure 3.11: Te Kuha Drill Log TK-19. Lithologic log reproduced from core data made available by CRL Energy. The conglomeratic facies below the BCM in the Mt. Rochfort section approximately 5km to the NE are absent at Te Kuha and a quartzofeldspathic grading to quartzose sandstone is instead present.

The contact with the overlying BCM was difficult to define (Pers. Coms. Aaron Dutton), but was placed within a 6m section of a granule conglomerate where there is a notable decrease in lithic content (Figure 3.11, 110m). Above this point are 45m of quartzofeldspathic coarse sandstones overlain by a thick coal seam and another 10m of quartzose sandstones at the top. These sandstones are very similar to the lower sequence also grading from coarse sandstone into siltstones over about 2-3 meter sections, but generally this section is coarser overall. All of these quartzose fining up packages are placed within the BCM (Dutton et al., n.d.).

Te Kuha's stratigraphy is, generally, representative of a fluvial meandering river and overbank floodplain setting. The coarser sandstones represent deposition within the meander channels and the fining up and eventual deposition of carbonaceous siltstones is representative of overbank floodplain deposition (e.g. Nichols & Fisher, 2007). The similarities to sedimentary facies recognized in the BCM explains why the area had previously been classified as BCM. Composition is the main defining feature between the BCM and PCM, with the PCM Te Kuha containing more lithics and being far more feldspathic. This is interpreted as being derived from a more immature sedimentary source and the whole section is likely older than the BCM in the rest of the Buller area.

#### *3.4.2. Mt. Rochfort – Te Kuha Transect*

The similarities in composition between the stratigraphy at Mt. Rochfort and Te Kuha suggested that they may be related. To assess any relationship the two areas may have with one another a lithofacies cross-section was constructed (Figure 3.12). This cross section uses the sections from Mt Rochfort (Appendix 3) and drill holes at Te Kuha (Appendix 2). They are hung off the main seam of the Brunner Coal Measures as it is confidently identified in all measured sections and drill holes and therefore a reliable datum. There is certainly some uncertainty about the area between Mt Rochfort and Te Kuha as there is no outcrop to trace from, but on the km scale that this cross section is drawn any error in correctly aligning the sections has a minimal effect on the overall interpretation.

The cross-section shows a gradual thickening of the combined Mt Rochfort and Te Kuha stratigraphy toward the NE and a rapid pinch out somewhere between Mt Rochfort and the Old Escarpment Mine to the north. South of Te Kuha the Buller River has eroded any strata that extended that way but it is inferred that there was also a gradual thinning in that direction (Figure 3.12)

The geometry and lithofacies represent what appears to be a textbook example of a half graben (e.g. Busby & Perez, 2012). The main fault is to the NE, likely with a NW-SE orientation, and the conglomeratic lithofacies are directly adjacent to this fault. To the SE in the Te Kuha Sector, the sandy PCM are stratigraphically equivalent to the conglomerate at Mt Rochfort (based on the BCM as a datum) and therefore a transition must occur somewhere between the two. The conglomerates extending off the fault scarp would therefore represent alluvial fan development with the sandstones at Te Kuha likely derived from along the basin axis or through incipient hanging wall drainage (Gawthorpe & Leeder, 2000). The rounded nature of the conglomerates suggests that they had been transported for some distance before depositing in the alluvial fan(s). They are not directly related to erosion of the fault scarp.

The orientation of this half graben is only an estimate. From the data available a NE-SW trend seems likely, though this is tentatively inferred. As the drill hole data and sections are mostly linearly spaced this is an apparent trend only. Unfortunately most of the strata has been eroded to the east and west so basin orientations inferred from isopach models are likely not possible.

One other important variable that should be considered is age. Currently no age data is available for the stratigraphy at Te Kuha or at Mt Rochfort (attempted by Titheridge (1992) but unsuccessful). It is my hope to ascertain some pollen ages from the cores at Te Kuha and possibly from samples from Mt Rochfort shortly after the completion of this thesis for later publication. However until such a time, the assumption that PCM equivalent strata are present in the southern Buller Coalfield (Dutton et al., n.d.) will remain inferred, based only on lithologic similarities and coal composition.

The prominent basal conglomerate at Mt Rochfort and newly identified probable Paparoa Group equivalent strata at Te Kuha were named for simpler differentiation. Originally for informal field based classification, the conglomerate at Mt Rochfort was conveniently named the Rochfort Conglomerate after the type location and the PCM like sediments to the south at Te Kuha were termed the Te Kuha Sandstones, also after the type location.

Compositional and stratigraphic similarities between the two though suggested that they were likely equivalents (Figure 3.12). With this in mind the informal names used during field work were revised into a new proposed stratigraphic nomenclature for the southern Buller Coalfield.



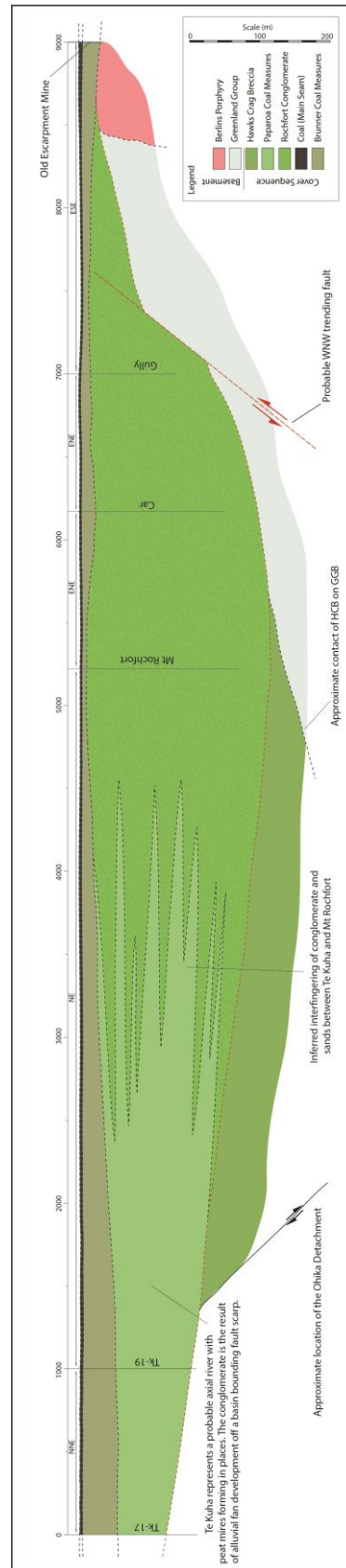


Figure 3.12: Schematic lithofacies transect of the stratigraphy between the Te Kuha and Mt Rochfort Sectors in the southern Buller Coal Field.

### 3.4.3. Southern Buller Basin Nomenclature Revision

A formation level of classification is proposed for this particular isolated occurrence of PCM like strata. The Papahaua Formation (after the Papahaua Range) is proposed as a new formation and contains the Rochfort Conglomerate and the Te Kuha Sandstones which are formalized into members. The Te Kuha Sandstones are now referred to as the Te Kuha Sandstone Member and the Rochfort Conglomerate is now the Rochfort Conglomerate Member. These two members together represent all of the PCM like strata below the Brunner Coal Measures in the Buller Coal Field. The Papahaua Formation is included within the Paparoa Group as a very northern outlier to highlight the similarities in lithology to the southerly examples but without suggesting a direct relationship with the Pike River, Greymouth or Punakaiki PCM.

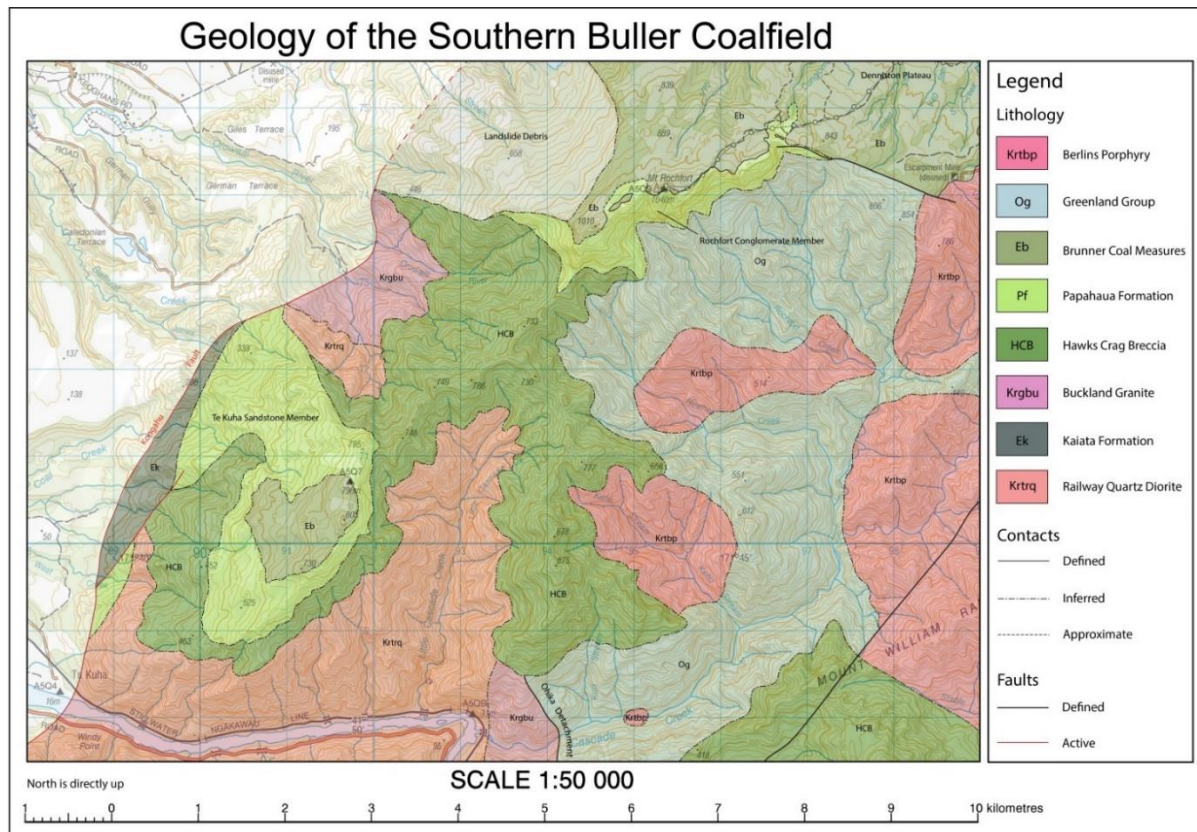


Figure 3.13: Revised geological map of the southern Buller Coalfield showing the extent of the Papahaua Formation and the relationship between the Te Kuha and Mt Rochfort sectors. Modified from Nathan (1978a; 1996) and Dutton et al. (n.d.).

With this new nomenclature, a revised map of the southern Buller Coal Field has been constructed to define the extent of the new formation (Figure 3.13). This map was produced

using existing maps of the Buller & Lyell and the Buller Coal Field areas (Nathan, 1978a; 1996 respectively), revised mapping of the Te Kuha sector in Dutton et al. (n.d.) and field and aerial photo mapping of the Mt Rochfort area conducted as part of this research (see Mt Rochfort section above).

### **3.5. Depositional and Tectonic History of the Southern Buller Basin**

The southern Buller Basin has a different depositional history to that of the northern Buller Basin. The BCM are not noticeably different here, but the newly defined Papahaua Formation of the Paparoa Group suggests a more active tectonic history prior to deposition of the BCM.

The Papahaua Formation is inferred to be the sedimentary expression of deposition within the Mt. Rochfort graben. The Te Kuha Sandstone and the Rochfort Conglomerate are formed from axial or incipient hanging wall drainage and alluvial fan deposition respectively. The location of the basin bounding fault is to the NE and inferred to strike approximately NW-SE. The orientation of the basin axis is also inferred to strike similarly.

The Papahaua Formation and thus the Mt. Rochfort basin are inferred to have formed in the same period (Late Cretaceous – Early Palaeocene) as the Paparoa Group further south (Dutton et al., n.d.). The Mt. Rochfort basin however has a different orientation from the NNE-SSW oriented basins further south (Gage, 1952; Newman, 1985; Cody, 2015). This anomalous orientation may be related to the NW striking mid Cretaceous age Ohika detachment fault of the Paparoa Metamorphic Core Complex, which runs directly under Papahaua Formation.

No direct evidence for reactivation of the Ohika Detachment is seen but movement on the detachment cannot be ruled out. Inferred to run directly between Mt Rochfort and Trig 5Q7 (Figure 3.13), the Papahaua Formation has been eroded through this area and any affect the detachment may have had on deposition is lost. Instead the inferred dominant fault of the Mt Rochfort basin is approximately 6km northeast. This fault is similarly oriented to the northwest dipping Ohika Detachment but dips in the opposite direction (inferred SW dip) (Figure 3.14).

It is unclear if the opposing dips between the inferred bounding fault of the Mt Rochfort Graben and the Cretaceous Ohika Detachment are related but their relationship is not considered to be a mere coincidence. The bounding fault may represent the reactivation of a preexisting conjugate normal fault of the main detachment or alternatively, reactivation of another Cretaceous graben bounding fault somewhere to the north of the current extent of the Hawks

Crag Breccia. In either case it seems that sometime during the Palaeocene the detachment was favorably oriented with the regional stress direction and likely saw some amount of reactivation (e.g. Nixon et al., 2014). The Papahaua Formation is therefore attributed to the influence and probable reactivation of this mid Cretaceous structure.

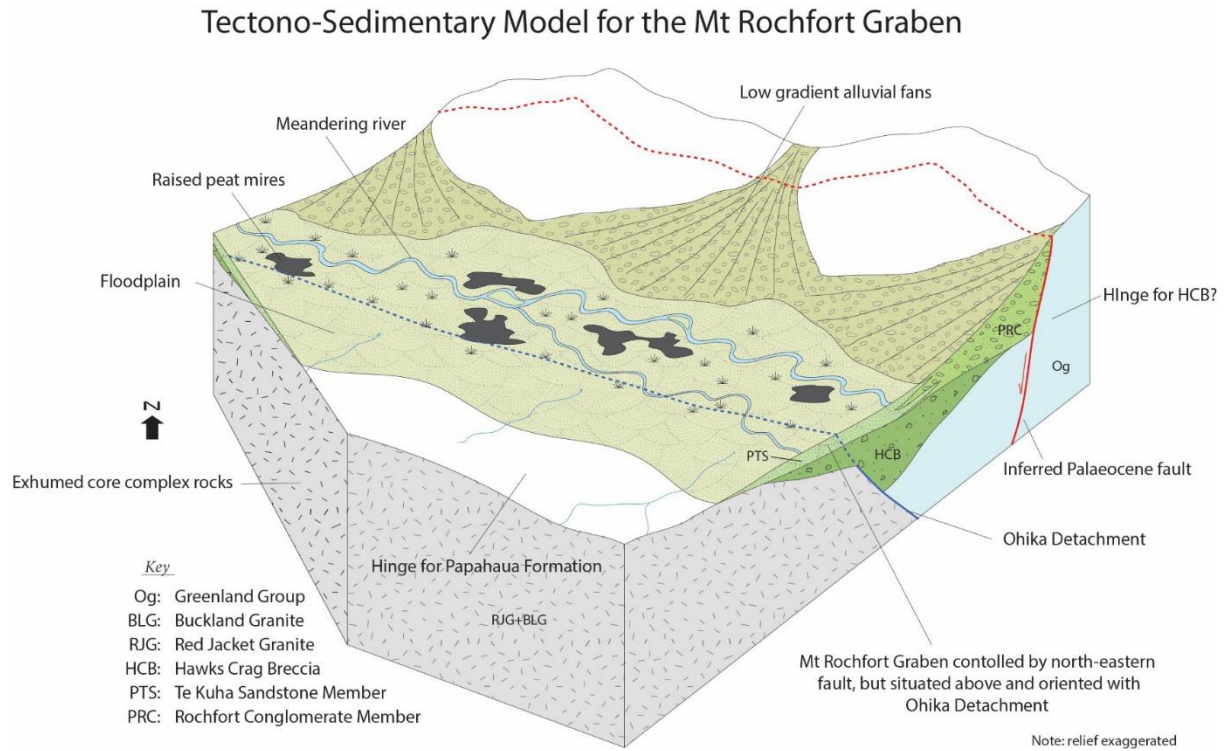


Figure 3.14: Tectono-sedimentary model of the Mt. Rochfort graben showing the inferred depositional and tectonic setting of the Papahaua Formation. The Rochfort Conglomerate is associated with an uplifted fault block to the northeast and the Te Kuha Sandstone is derived from axial and incipient hanging wall drainage. Note the relationship of the basin orientation and location to the underlying Hawks Crag Breccia and the Ohika Detachment Fault.

### 3.6. Conclusions

The Middle Eocene period of Buller Region is characterised by a thick (30- up to 60m) succession of the quartzose Brunner Coal Measures. These sandstones, siltstones and coals were deposited within a gradually subsiding basin as part of a meandering river floodplain. Marine transgression which accompanied subsidence resulted in deposition of marginal marine facies toward the top of the BCM and eventual drowning saw the beginning of marine

sedimentation (Flores & Sykes, 1996). Deposition was also partially controlled by syndepositional faulting. This is recognized as having an effect on deposition of the BCM by Titheridge (1993) and myself, but much more prominently in the older (inferred Late Cretaceous – Early Palaeocene from Dutton et al., n.d.) Papahaua Formation, defined for the first time in this thesis. This older period of faulting is oriented almost perpendicular to other faults known to be active during this time but aligned with, and located directly above an older mid Cretaceous structure. For this reason reactivation of faults associated with the Ohika Detachment is inferred to have occurred in the Late-Cretaceous or Early Palaeocene) and had controlled deposition in the Buller Region at this time.

## **Chapter 4 The Charleston Region**

### **The intervening plains**

#### **4.1. Introduction**

The Charleston region contains generally the thinnest Brunner Coal Measures (BCM) and deepest weathering profile encountered during research. The Charleston region represents the majority of BCM outcrop outside of the Buller and Greymouth basins so is a vital link between the two isolated areas. In comparison to the Buller and Greymouth coal fields, little recent research has been conducted on early Cenozoic strata in the area. Therefore the information herein is either original to this project, or the work of previous authors from at least 30 years ago.

The boundaries (figure 1.1) for this region extend from Cape Foulwind in the north to just south of Punakaiki. Included within the coastal region are two locations from the east side of the Paparoa Ranges. These outliers are grouped with the coastal region based on stratigraphic similarities and also being between the Buller and Greymouth Regions.

In the northern part of the region outcrops of the BCM and basal unconformity are scattered along the coastal strip in the foreland of the NNE trending Paparoa Ranges. The strata here dip gently ( $10^{\circ}$ ) to the east and, based on the rank of coal, have undergone significantly less burial than in the two previously discussed regions (Nathan 1972; 1975). Further south the BCM are exposed in cliffs and scarps along State Highway 6 until 5km north of Punakaiki where they appear to pinch out (Laird et al., 1988). While exposures are harder to find, the trend of a gentle dip prevails but with some slight deformation from the Punakaiki Anticline either tilting the strata to the west or remaining near horizontal. In the ranges behind Punakaiki a thin strip of BCM is poorly exposed but extends for approximately 6km at the base of a thick Cenozoic Sequence. The unit is faulted at either end so its relationship to the apparent thinning 5km north is not known.

##### *4.1.1. Methodology*

The approach used in the Charleston Region, like Greymouth and Buller, relies heavily on sedimentary description and classification. A series of measured sections, palaeoflow measurements, clast counting and thin section analysis was used to detail the stratigraphy

across this broad region. Due to the size however, many locations relied on the work of previous authors. These are therefore included in a separate section to the work carried out as part of this research.

## **4.2. Key stratigraphic sections for the Charleston region.**

The following sections detail the stratigraphy of the Charleston region heading from north to south. Field work in this area was focused on the BCM exposed north of Punakaiki and providing a general overview for the region. Some areas that were not visited during field work are included. These locations utilize the work of previous authors, both data and interpretations, although my own interpretations are often included and specifically stated.

### *4.2.1. Cape Foulwind*

A thin outcrop of BCM in the railway cutting at Cape Foulwind is the most representative outcrop for the northern part of the Charleston region (figure 1.1). The section is poorly exposed and to locate the unconformity the face had to first be cleared of vegetation. The rest of the outcrop is still covered and not well documented. The unconformity here is developed on the Carboniferous Cape Foulwind Granite (Tulloch et al. 2009) and has some peculiar characteristics not seen elsewhere.

Beginning 16m below the unconformity (figure 4.1), the granite is found to be soft, and produces a dull thud when struck with a hammer. Up section for 10m the granite is not visibly altered until 6m below the unconformity where alteration can be seen with clay replacing feldspars throughout the rock mass. For 2m further the granite becomes progressively more altered and 4m below the unconformity can be broken (with some difficulty) by hand. At this point much of the rock mass is constituted by soft grey clays but texturally still resembles the unaltered granite from below. At 2m below the unconformity a light grey clay layer containing abundant angular quartz fragments is recognized as infilling opened joints in the granite. The top 1m of the granite is totally comprised of this clay but with numerous highly altered corestones contained within. The unconformity itself is not easy to identify but appears parallel to bedding in the overlying strata. There is certainly some undulation along the surface, up to 1m from what can be seen in outcrop and visibly down cuts into the grey clay at the upper center left of figure 4.1, C.



The sequence below the unconformity is interpreted as a well-developed and thick weathering profile (figure 4.1). The clay rich upper portion of the profile resembles a residual soil, no characteristics of the parent rock are preserved representing complete weathering of the granite body (e.g. Borrelli et al, 2014). The section of corestone and joint controlled weathering is a common feature in granitic weathering (Kirschbaum et al, 2005; Martini & Chesworth, 1992). This section shows discoloration, alteration of unstable minerals and a lack of strength yet still displays characteristics in common with the parent rock. The transition from completely weathered at the top to moderately weathered at the base is interpreted to approximate the vertical extent of intense surface pedogenesis (e.g. Kraus, 1999). The remaining granite body is moderately weathered, becoming increasingly less weathered down section. The 25m minimum thickness of the altered granite indicates that soil development was a major feature of the landscape prior to deposition of the BCM.

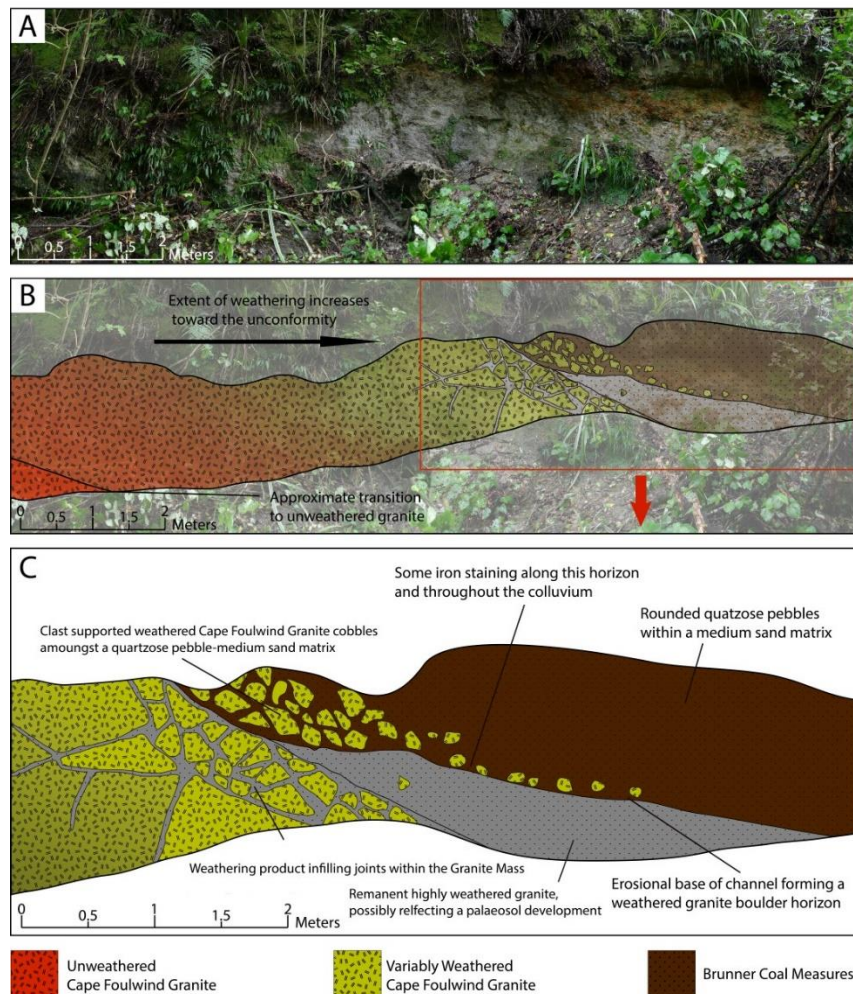


Figure 4.1: Cape Foulwind railway cutting showing the outcrop of the Brunner Coal Measures, the basal unconformity and the weathered granite below.



Directly above the unconformity, there is a layer of highly angular, cobble to boulder sized, weathered granitic clasts within a quartzose pebble conglomerate to coarse sandstone. These are clast supported to the west (left in figure 4.1) but intermittently scattered at the base of the sandstone to the east. Based on the angularity and composition they are derived from the basement granite and have likely been transported only a very short distance, if at all. These boulders are interpreted to be core stones like below the unconformity but the soft clays have been removed through fluvial erosion and replaced with the quartzose sandstone. The geometry of boulders to the left of Figure 5.1, C may represent a colluvial deposit derived from bank collapse further to the west (left) (Bridge, 2003). A small stream down cutting into basement (e.g. Tinkler & Wohl, 1998) in this location explains the removal of the upper clay layer to the right and a cause for bank collapse to the left. Erosion accompanying this channel development is also interpreted to have formed the undulation of the unconformity.

All that can be seen in the poorly exposed section overlying the unconformity is a rounded, moderately well sorted quartzose sandstone. On close inspection some fining up sequences can be observed with pebbles abruptly grading up into medium sandstone but no cross bedding or bar forms are visible. The outcrop is interpreted to represent fluvial channels of either a sandy braided river or a low sinuosity meandering river (e.g. Boggs, 2012).

The top of the BCM is not seen, hence the thickness here is uncertain. At the very end of the railway cutting the topography changes abruptly and drops off down towards Gibsons Beach. This change is inferred to approximate the location of the BCM-Kaiata Formation contact and puts the thickness at around 10m. A possible transition from a yellow, poorly indurated medium sandstone into a laminated grey fine sandstone at the very end of the cutting may represent the change from fluvial to a transitional facies, such as delta or estuarine (e.g. Bhattacharya, 2010), or simply be a thin overbank deposit within the coal measures (e.g. Miall, 2010). Equally the contact may be wave cut and an unconformity might separate the two units with no transitional facies occurring (e.g. Plint, 2010). As for the development of peat mires, no coal is seen in the railway cut but 2km south on the beach at Tauranga Bay an outcrop of lignite is occasionally visible after big storms scour out the beach gravels (Nathan, 1975).

The BCM at Cape Foulwind have been palynologically dated as Late Eocene (Kaiatan Stage) (Nathan, 1976). This is somewhat later than the general Middle Eocene (Bortonian Stage) age indicated for the BCM over most of the study area. Deposition at Cape Foulwind therefore

occurred after the majority of the BCM had already been deposited in the Buller and Greymouth Regions.

#### *4.2.2. Morrisey Creek and inland of Needle Point*

The Morrisey Creek section, which serves as the type section for the central coastal portion of the Charleston area, was constructed from two outcrops roughly 3km apart (figure 1.1). Outcrop 1 shows the basal contact detailing the basement weathering, unconformity and lithologies below the prominent coal seam whereas outcrop 2 shows the top of the section overlying the coal seam to the Little Totara Sand, an equivalent of the Island Sandstone for the Charleston region (Laird, 1988). The overall thickness of the BCM here is only about 20m.

The lower part of the section from around the remnants of the Sunshine Opencast Mine, contains a deep weathering profile developed into the gneissic/mylonitic basement (figure 4.2). This weathered horizon extends for at least 8m down from the unconformity before it is no longer exposed. Based on another outcrop approximately 1.2km south, coherent rock is probably not reached for at least another 5-10m for a total weathering depth of 13-18m. The unconformity itself is not seen directly but is located to within a 1m interval where the outcrop has some minor slumping. The orientation of the unconformity is consistent with the bedding orientations observed in the strata above and no major undulation of the surface is recognized.

Basement here is the Pecksniff Paragneiss of the Charleston Metamorphic Group. At the lowest stratigraphic point before outcrop is lost the gneiss is visibly compositionally banded and shows little sign of alteration but produces a hollow thud when stuck with a hammer. Approximately 2m below the unconformity rock becomes soft and can be broken by hand with difficulty. Aside from quartz layers, compositional bands are more difficult to recognize and the outcrop has a whiter bleached appearance. Directly below the unconformity the gneiss is light greeny grey and soft enough to be easily dug into by hand; only the quartzose compositional bands maintain any strength and protrude from the outcrop.

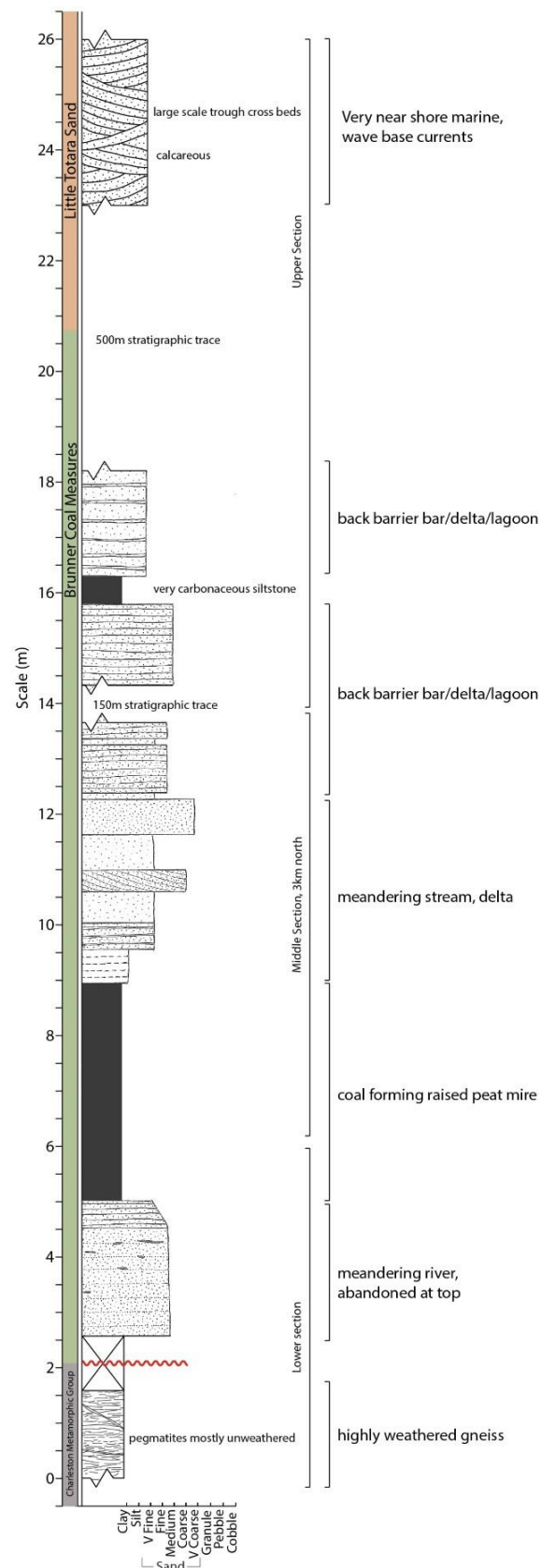


Figure 4.2: Morrissey Creek Section. Lower section is approximately 3km south of the middle and upper section. Correlation made using the coal seam present in both outcrops.

This weathered horizon is attributed to intense soil development but with some different characteristics due to the rock type being weathered. The gneissic basement does not produce corestones or prominent joint controlled weathering since it is generally without jointing and fracturing (Borrelli et al, 2014). This explains the consistent decrease in degree of weathering away from the unconformity as without such discontinuities the gneiss weathers uniformly. The loss of micro textures in the upper 2m below the unconformity is an indication of significant chemical weathering (Martini & Chesworth, 1992).

There is no clay rich residual soil directly below the unconformity at this locality which can be attributed to one of three possibilities. 1. It is somewhere within the 1m section not well exposed. This is unlikely as such a distinctive layer would be easily recognizable in contrast to the very similar weathered gneiss and quartzose medium sandstone present, despite the complication of the slumped outcrop. 2. The layer never formed. Perhaps in this area pedogenesis was limited and a horizon of complete alteration of the gneiss did not occur. Finally, 3. A clay rich residual soil did form but was subsequently eroded with deposition of the BCM. Scenarios 2 and 3 are both possibilities with 3 the most likely.

Resting on the unconformity is a very poorly exposed grey, well rounded medium quartzose sandstone with numerous coaly stringers toward the top. Up section this medium sandstone grades into a thin (0.5m) carbonaceous fine sandstone and itself into a coal seam of up to 3m thickness. The coal appears clean within no detrital component recognized. Data on ash content from Coal Resources of the Charleston Area (Nathan, 1972) confirmed this.

The lower portion of this section is speculatively interpreted as a fluvial deposit, probably the channel of a small meandering river. Abandonment of the channel and subsequent infilling with fine grained organic rich sediment in a low energy, possibly ponded environment, formed the layer of coaly stringers and carbonaceous fine sandstone at the top (e.g. Bridge, 2003). The formation of peat through further accumulation of organic matter continued for a significant period after channel abandonment for the greater than 2m thick coal seam to form. The clean nature of the coal suggests the peat was formed as part of a raised mire which limited flooding by proximal streams and rivers (Esterle & Ferm, 1994).

At this point overlying layers had been eroded from the outcrop and the coal seam was used to correlate with the 2nd road outcrop 3km north and inland of Needle Point (figure 1.1). The coal seam itself may not be continuous over this distance but modern analogues of similar raised mires are often laterally expansive covering many 10's of km (Robinson & McCabe, 1992).

The coal is used as a marker bed based on this interpretation and allows correlation between the two outcrops.

Above the coal seam, which here at the 2<sup>nd</sup> outcrop is at least 3.5m thick, a meter and a half of carbonaceous siltstone grades into a laminated and then featureless fine sandstone (figure 4.2, 9m). In places the laminations in the sandstone appear to be paired. This is truncated by a thin, 40cm thick, coarse to very coarse, tabular cross bedded sandstone indicating a westward palaeoflow direction. A similar layer of very coarse sandstone occurs just up section but this unit was recognized to have a lenticular shape across the outcrop suggesting a channel developed into the underlying lithologies but with no cross bedding recognized. The remainder of the outcrop was a poorly exposed carbonaceous laminated fine sandstone. Sulfur staining of the surface was present in all the outcrop above the coal.

The outcrop was correlated with another exposure across a valley 150m north which began with at least 1.5m of the same carbonaceous laminated fine sandstones. Above this, a 0.5m seam of carbonaceous siltstone crops out and is then followed by at least 2m of yellow laminated fine/very fine sandstone with paired carbonaceous laminations in places. This sandstone fizzed very slightly thus it is inferred to be partly calcareous. 500m to the north the distinctive trough cross bedded, well sorted, quartzose, calcareous, medium – coarse sandstone of the Little Totara Sand (Nathan, 1975) is seen in a road cut. No outcrop is present between these two exposures but based on the dip of the upper yellow laminated sandstone, the Little Totara Sand is probably no more than 5-10m stratigraphically above.

The thick coal and organic laminations place the environment as terrestrial, but with a tidal influence as paired mud drapes indicate tidal influence almost directly above the coal (e.g. Dalrymple, 2010). Coarser channel sandstones and a probable point bar indicated by the planar cross bedded sandstone are inferred to represent deposition in a meandering river/stream. These occur within the tidally influenced sandstones suggesting that deposition was likely in a lagoonal, lower delta or upper estuarine environment. Saline water does not allow true peat formation hence why the upper very silty coal (or possibly very carbonaceous siltstone) is inferred to be transported rather than accumulated in situ. In this case there is no need for a fresh water environment and deposition about the coal can still be influenced by tides (Reading, 1996; Dalrymple, 2010). The sulfur staining throughout the outcrop is attributed to the marine incursion that immediately follows the coal. Sulfur leaching due to marine influence is common in other occurrences of the BCM (Flores & Sykes, 1996). Evidence of wave and or current

influence is only observed in the Little Totara Sand road cut with grainsize sorting and trough cross beds likely forming as part of sinuous migrating dune in the submarine near shore environment. The approximate thickness of terrestrial strata for the combined stratigraphic column (figure 4.2) is around 20m.

It is important to note that Nathan (1975) classified the majority of the strata above the coal seam at Sunshine Open Cast (the lower section of figure 4.2) as the near shore marine Little Totara Sand. While this is not the exact same section, based on my field observations, what was called Little Totara Sand here may have actually been more of a transitional facies of the Brunner Coal Measures with the gradational change into the marine Little Totara Sand occurring further up section.

#### *4.2.3. Morrissey Creek (Palaeotopography)*

A road outcrop located just around the corner from the lower part of figure 4.2 at Sunshine Open Cast (figure 1.1) displays an excellent example of preexisting topography prior to the deposition of the BCM (figure 4.3). This outcrop is faulted by a probable Miocene dextral oblique normal fault but the observed palaeotopography is not attributed to this feature.

The unconformity is developed into the Pecksniff Paragneiss of the Charleston Metamorphic Group (Nathan, 1975), a member of a series of lower crustal rocks exhumed through extension during formation of the mid Cretaceous Paparoa Metamorphic Core Complex (Ring et al., 2014). A deep weathering profile has developed in the Pecksniff Paragneiss for at least 5m below the unconformity, degrading much of the unstable mineral content into clays (figure 4.4). Directly below the unconformity a highly weathered horizon of not more than 75cm is composed entirely of clay. This horizon is interpreted as the upper portion of the weathering profile as a result of intense leaching from above (e.g. Elias & Mock, 2013).

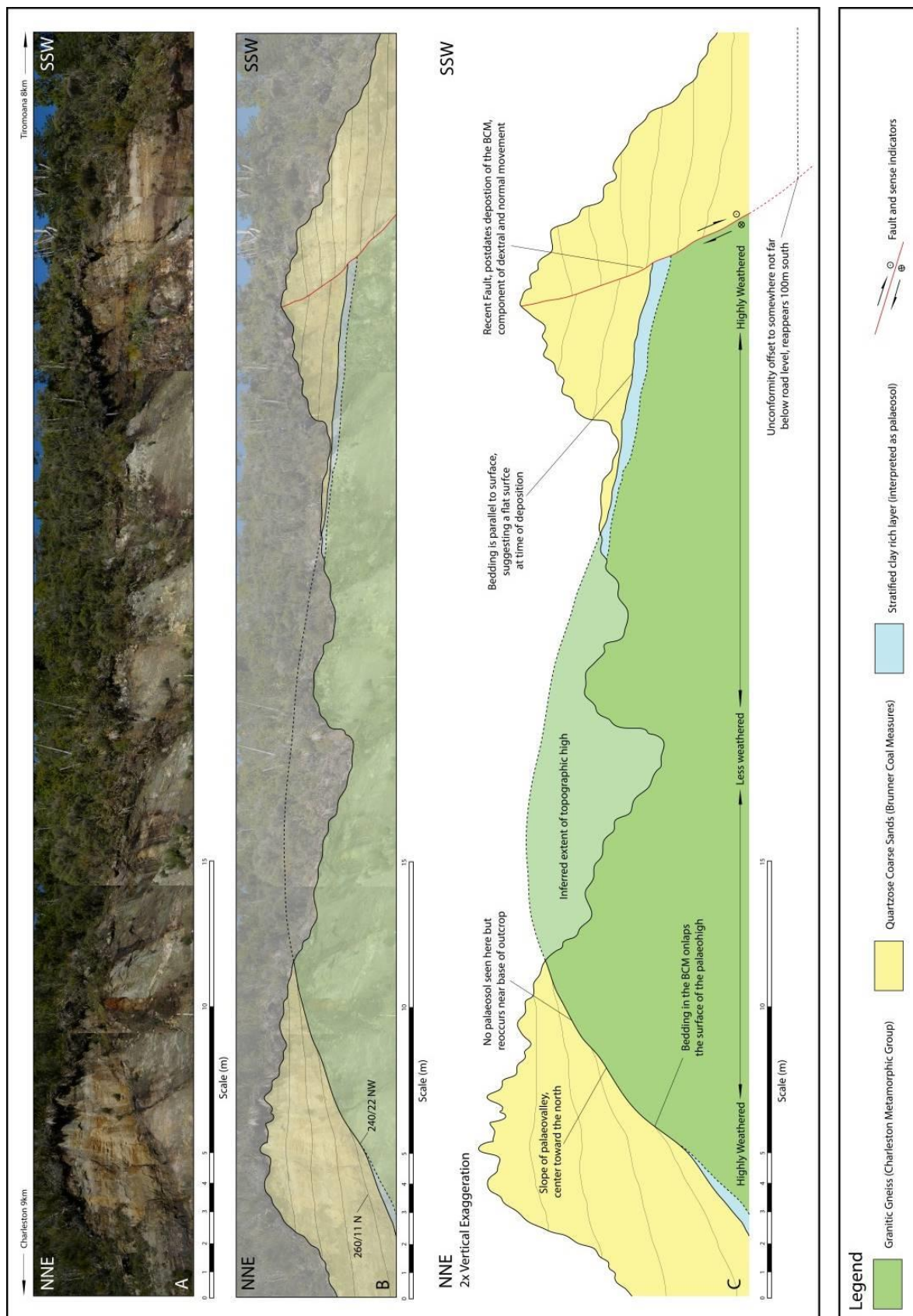


Figure 4.3: Morrissey Creek road cut showing palaeotopography on basal unconformity



Directly above the basement unconformity, on the southern end of the outcrop (but north of the fault), there is a quartzose, sparsely bedded, coarse sandstone. This sandstone grades normally into a very fine sandstone/siltstone then up into a thin coal seam. Above the coal there is a return to a medium to coarse quartzose sandstone with planar (Tabular) cross bedding just observable at the top of the exposure. The right side of the outcrop appears to represent a horizontal surface at the time of deposition. No geometric relationship, other than being parallel, is seen between bedding in the BCM and the unconformity. The highly weathered horizon below the unconformity also shows no signs of thinning or scouring expected if the surface was sub horizontal during deposition.



Figure 4.4: Upper highly degraded gneiss. The unconformity is marked by the dark sandstone with basal pebble quartz conglomerate in the top left. The grey layer is a soft clay and contains scattered angular quartz fragments throughout.

The north side of the outcrop is dominated by a similar, thick, quartzose succession of tabular cross bedded, coarse sandstones but with a carbonaceous siltstone and thin angular quartz pebble to cobble conglomerate layer at the base. The highly weathered clay rich layer here is only present at the base of the outcrop, thinning out roughly 2.5m above road level. Bedding in the north of the outcrop is seen to onlap the basement unconformity but is mostly parallel to the weathered clay layer.



Correlation of beds in the southern section of the outcrop was made with beds in the north during the field investigation. Based on the geometric relationship between bedding orientations in the two sections the base of the southern section would likely equate to the upper 2-3m of the northern section. This leaves at least 4m of channel fill material below the assumed correlative reference level. The north side of the outcrop is therefore interpreted to represent a small palaeovalley. The conglomeratic layer at the base of the coarse sandstone indicates a higher energy depositional environment here in comparison to the strata to the south. The onlap of beds in the BCM also supports the presence of a slope dipping northward toward the palaeovalley. The lack of the clay rich highly weathered horizon on the slope of the inferred palaeovalley could either reflect a lack of intense soil development on the steeper section of the slope, or erosion by the overlying strata during deposition. While the outcrop does not continue to the north, I'll note that the slope of the palaeovalley does appear to flatten out so the total depth is likely not too much greater than the minimum 4m calculated.

#### *4.2.4. Fox River*

The lower reaches of the Fox River and the coastal exposures in the immediate vicinity host a near complete Cenozoic transgressive sedimentary sequence and are used as the type section for the Fox River area. The mid Cretaceous Hawks Crag Breccia (HCB) is exposed at the Fox River mouth, presumably sitting upon the Meybille Granite not too far below the surface. The BCM are found directly overlying the HCB but the exact location and nature of the contact is not visible. Above the 40-50m thick BCM is a thick section of the Kaiata Formation capped by equally thick limestones of the Nile Group (Wellman et al., 1981). These thickness anomalies in the Kaiata and Nile Group are at odds with what is recognized elsewhere in the region (Laird, 1988; Riordan et al. 2014). Upon review of the existing literature it became apparent that the BCM at Fox River are also supposedly thicker than elsewhere along the coast (Wellman et al., 1981; Riordan et al., 2014).

The exposure of the BCM along the Fox River is approximately 1.5km upstream of the highway bridge on the true right of the river (figure 4.5). Here, a 25m cliff has formed in response to the river undercutting the northern bank and exposed a terrific section of lower Cenozoic strata, the majority belonging to the BCM.

The unconformity between the BCM and the Hawks Crag Breccia was not exposed in the cliff and must lie somewhere stratigraphically below (figure 4.6). To make the section useable in

later interpretations a thickness of the unexposed section was required. A maximum estimate was made using the dip of the beds in the cliff ( $9^{\circ}$ - $10^{\circ}$ ) with the distance between the last observable BCM and the first occurrence of the HCB (140m downstream) to work out the stratigraphic thickness between them. This was calculated to be  $9.7 \pm 1$ m. When added onto the observed thickness in outcrop, the BCM is at a maximum no more than 25m thick in the Fox River area. Considering the true thickness is probably less than this estimate, the claim from previous authors of an anomalously thick section of BCM (Wellman et al., 1981; Riordan et al., 2013) seems incorrect.

The base of the exposed section is comprised of a minimum 4m thick, quartzose, well rounded, moderately sorted, coarse sandstone with numerous coaly stringers increasing in frequency up section. A thin truncated medium sandstone is present within the coarse sandstones and highlights the lenticular shape of the coarse sandstone above. The sandstones below the coal are interpreted as multiple wide meander river channels from the lenticular shape and truncating relationships (e.g. Miall, 2010). The coaly stringers represent organic debris, either remobilized peat or plant matter, deposited as part of the channel fill material in a waning flow or during channel abandonment.

Above the coarse sandstone there is an immediate transition to a prominent coal seam. Based solely on outcrop description the coal appears clean; no observable detrital grains were seen in the main part of the seam and the coal has a bright vitreous luster. The coal, at 2m in thickness, is interpreted to be the result of a substantial and long lived peat mire. The lack of sediments entrained in the coal suggests that it was not at all impeded by fluvial or lacustrine processes and therefore likely raised above the surrounding land (Esterle & Ferm, 1994). No grading at the base of the coal from the coarse sandstone below is seen. This sharp contact suggests abandonment of the river channel immediately followed by accumulation of organic matter and peat formation.

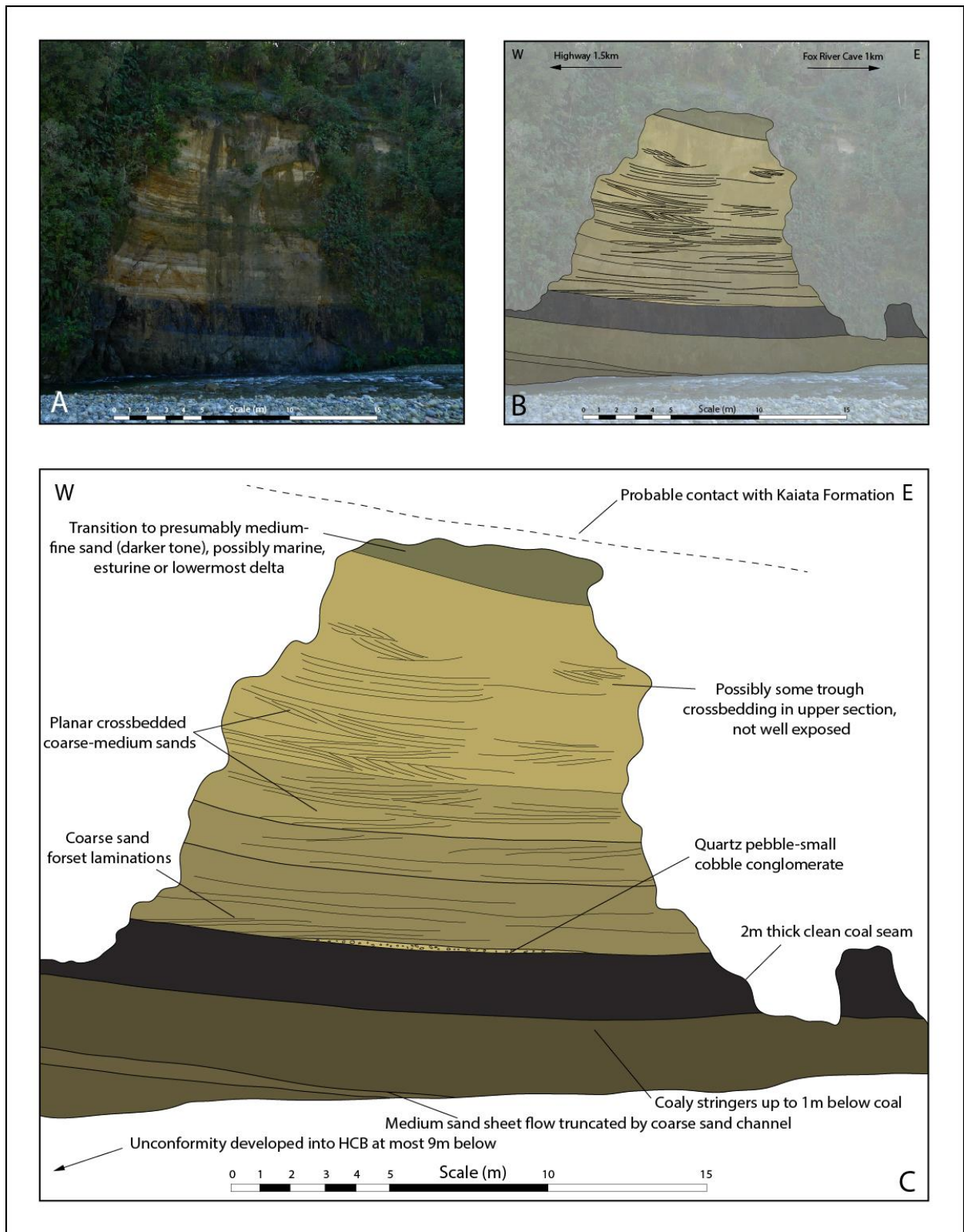


Figure 4.5: Fox River outcrop interpretation. The majority of the BCM are exposed in this one outcrop, the unconformity with the HCB is no more than 9m below the river level and the Kaiata Formation can be seen poorly exposed in the uppermost section of the cliff.

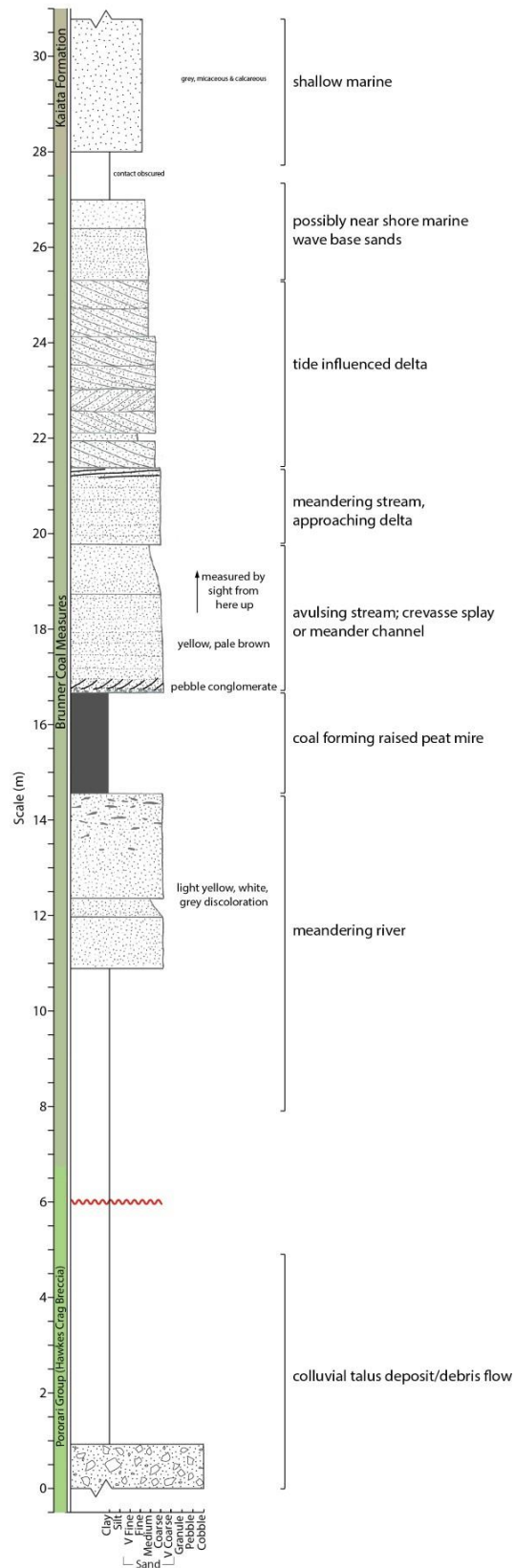


Figure 4.6: Fox River Section. Note that the unconformity between the BCM and the HCB is an estimate only due to the limitation of outcrop.

Above the coal seam is a 2m thick section of light yellowy brown, quartzose, coarse sandstone with some planar cross-bedding in the lower portion. The very base of this unit is occupied by a layer of angular quartz pebbles to small cobbles that rest directly on the coal with an erosional contact. A half meter section of coarse sandstone foreset laminations or lateral accretion deposits lie directly above this thin pebble layer, if the former they would indicate an approximate palaeoflow direction to the west. The remainder of the unit is dominated by faintly horizontally bedded coarse sandstones which then grade into a 1m thick, light brownish grey, normally graded, coarse to medium sandstone unit. Overall this segment resembles a prograding delta front, probably in the form of a crevasse splay, avulsing through the peat mire and as energy decreases the section fines upward (e.g. Miall, 2010).

Beyond this point the section (figure 5.6, 18m) was only observed from a distance due to the outcrop being inaccessible in the cliff overhead. Therefore the accuracy of measurements and classification of the strata within the section are only best guess estimates.

Directly above the normally graded sandstone unit is another 1.5m of bedded coarse sandstone which resembles the lower coarse sandstone unit. Upward for roughly 3m the section fines upward to be dominated by planar cross bedding with varying orientations in assumedly a coarse to medium sandstone. This is interpreted as the migration of a channel into this location or possibly another, or multiple, crevasse splay deposits. The cross beds indicate variations in flow direction but without physically measuring their orientations the amount of variation is uncertain. Potentially the depositional environment could be becoming more of a near coast setting in a delta or upper estuary (e.g. Bhattacharya, 2010; Boggs, 2012).

Up section from the cross bedded sandstones the outcrop is particularly difficult to observe. There appears to be another 1m of horizontally bedded coarse/medium sandstone and a half meter of featureless coarse/medium sandstone. Roughly 1m further up across a small band of vegetation the distinctive grey fine micaceous sandstone of the Kaiata Formation occurs, a fallen block of the unit confirming this identification. The upper boundary of the BCM is placed at the top of the outcrop somewhere in the vegetated cover. The transitional facies expected between the lower fluvial sandstones and the Kaiata Formation (Boyd, 2010) may be represented by the vegetated cover but without being able to observe the top portion closely this cannot be confirmed.

As stated previously the basal contact with the HCB is not seen, thus the presence or absence of weathering profile developed into the surface is unknown. It is also important to note that

the portion of the section above the coal seam was not accessible and the possibility of the upper cross bedded units being of marine origin, and thus belong within the Little Totara Sand, cannot be ruled out. If so, the thickness of the BCM in this area would be even thinner than the maximum estimate of 25m.

The BCM at Fox River do not have any definitive age data. The marine strata immediately above have been dated as Late Eocene (Kaiatan stage) using foraminifera but the BCM have as yet only been inferred as Middle Eocene (Bortonian stage) (Wellman et al., 1981). This is a tentative age used in later palaeogeographic reconstructions.

#### *4.2.5. Burley's Mine*

The Burleys Mine section (figure 4.7) was obtained from the headwaters of Fletchers Creek on the eastern side of the Paparoa Ranges, 20km south of Inangahua (figure 1.1). This places the section approximately in the same latitude as the rest of the Charleston region just on the eastern side of the younger Paparoa Trough.

The section is measured through a thin strip of BCM intermittently present at the base of the Cenozoic succession in this area (Nathan, 1978; 2002), in this case in the abandoned Burley's Mine open pit. Fortunately, the highwall has been left uncovered since it was abandoned allowing great exposure of the lower Cenozoic sequence. The section covers the entirety of the BCM, from highly weathered granitic basement through to the lower-most Kaiata Formation. The remaining Cenozoic sequence is exposed along the access road and in Fletcher Creek itself. The stratigraphic column in figure 4.7 details the stratigraphy within the mine site from the basal contact up to the Kaiata Formation.

Basement is the Blackwater Granite of the Rahu Suite (Nathan, 2002) and is highly weathered for several meters down. A poorly exposed light grey clay is present for 90cm below the unconformity then a sharp change into soft, nearly completely degraded granite occurs. Unfortunately no samples of this clay horizon were taken and on a return to the site the area has since been covered in a slip. The granite below is recognized as near completely weathered. It is broken by hand but visually retains original microtextures from the parent rock.

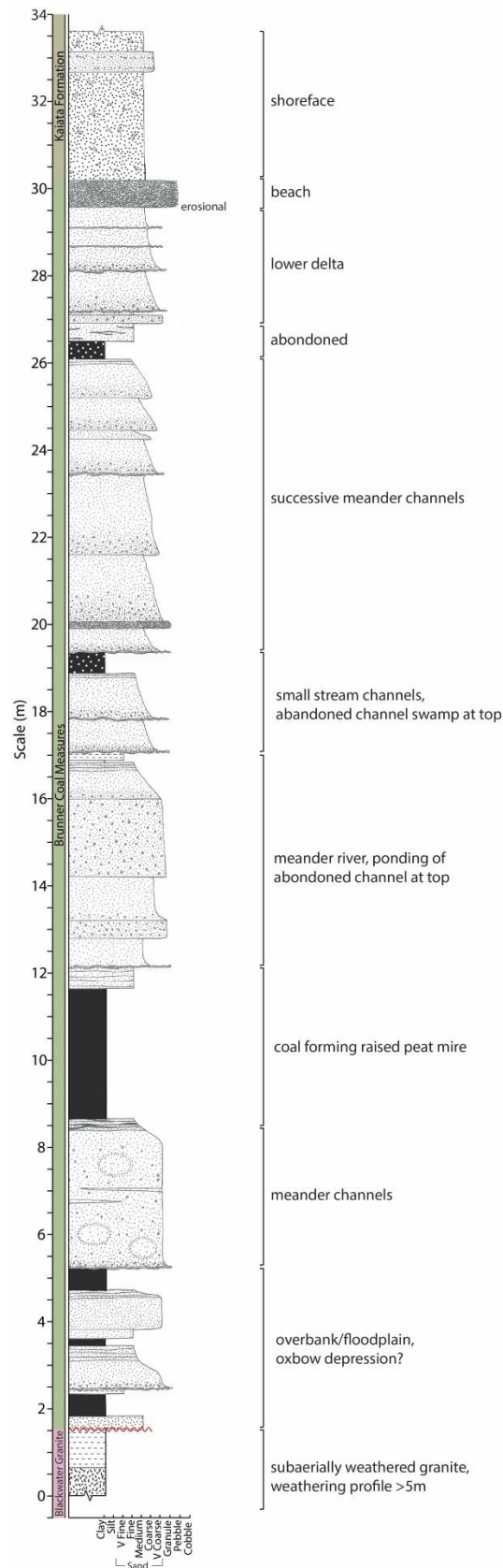


Figure 4.7: Burley's Mine Section showing a series of stacked meander channels, overbank, oxbow and coal facies of a meandering river floodplain system, including the transition into a marine setting at the top of the section.

The total thickness of the weathered granite is unknown but it extends for at least 5m from what is exposed in outcrop. The degraded granite and clay are interpreted to represent a deep weathering profile. The clay itself could likely be classed as an argillisol using the palaeosol classification of Mack et al (1993), derived solely from in situ weathering of unstable minerals within the granitic undermass.

The unconformity is only seen in a few small gullies eroding a scarp in the footwall of the mine. The surface appears planar with no apparent undulation or down cutting into the clay horizon directly below.

Above the unconformity there is a 3.5m section of silty coals with interbedded fining up, coarse to fine sandstone beds (figure 4.7). The coals are thin (0.5m) and in places are more carbonaceous siltstones due to the high percentage of included sediment. The tops of the silty coals are truncated by very coarse to coarse sandstone layers (1m thick). This interbedded unit is interpreted to represent an overbank/floodplain setting where peat formation is intermittently disturbed by flood events and deposition of the fining upward sandstones in proximal crevasse splays (e.g. Miall, 2010).

Up section, a thick very coarse sandstone with a basal pebble lag and containing numerous concretions up to 1m in diameter overlies the coal. The very coarse sandstone normally grades into a carbonaceous, laminated, fine sandstone at the top with abundant coaly stringers in the uppermost 50cm. The fining up sandstone unit is lenticular in shape when traced across the mine footwall (greater than 25m) thus is interpreted as a channel; presumably belonging to a meandering river based on the normal grading and association with floodplain coal beds.

The carbonaceous laminated fine sandstone grades into a 3m thick seam of clean coal. The lack of sediments entrained in this coal suggests that the peat accumulation was not interrupted by fluvial processes and therefore the mire was likely raised above the surrounding floodplain (Robinson & McCabe, 1992).

The top of the coal is conformably overlain by a 50cm layer of laminated carbonaceous siltstone overlain by three fining up sequences of very coarse sandstone to siltstone and occasional shaly coal over the next 15m. The lower most of the fining up sandstone sequences truncates the top of the laminated siltstone above the coal below. A thin lag of rounded pebbles is present on this surface at the base of a 50cm layer of medium-coarse sandstone. This unit itself is truncated by a very coarse to granule sandstone that normally grades into a coarse sandstone above. A similar pattern of truncation by subsequent normally graded units is present



throughout the 15m interval. The basal siltstone likely represents the first incursion of flooding into the peat mire as the floodplain aggraded (e.g. Bridge, 2003). The numerous fining up sandstone units are interpreted as repeated meandering channel migration across a floodplain (e.g. Miall, 1996; Bridge, 2003; Miall 2010). Very fine sandstones, carbonaceous siltstones and shaly coals represent a temporary low energy floodplain depositional environment, probably resulting in a swampy setting after channel abandonment (Boggs, 2012).

Above the top most shaly coal and carbonaceous fine sandstone there is an abrupt change to a 2.5m thick section of stacked, normally graded, lenticular sandstone beds. Each bed starts with a basal layer of well sorted and rounded pebbles fining up to very well rounded, coarse to medium sandstone and while thinning across the outcrop, their lenticular shape extends for at least 40m. These beds are interpreted to represent thin (0.5m) but very wide low gradient channels of a river, possibly within a prograding delta (e.g. Bhattacharya, 2010). The minimal thickness of the normally graded lenticular sandstones represents rapid and frequent avulsions of small channels and the pebble layers are the result of the initial migration and coarse bedload deposition (Reading, 1996; Miall, 2010).

An erosional contact at the top of the probable delta facies leads into an unmistakable deposit of a gravelly beach (e.g. Boyd, 2010). Only 50cm thick, this layer is solely composed of well rounded, well sorted, clast supported quartzose pebbles that appear stacked or imbricated. There is no apparent matrix constituent (with the exception of a siliceous cement) and the layer is obviously very porous as groundwater was constantly flowing out of the bed. A grey medium sandstone with scattered shell fragments overlies the conglomerate and extends up section for at least 10m. A 50cm coarse sand-granule layer 2.5m up from the base is the only distinguishably different feature in this unit. This is inferred to be the lowermost and very near shore portion of the marine transgressive sequence, which in this area is classified as the Kaiata Formation (Nathan, 1978a). No Little Totara Sand, Island Sandstone or other near shore/transitional formations are currently classified here (Nathan et al., 2002).

Over all the BCM at Burley's Mine are no more than 28m thick. The sedimentary facies mostly resemble what is seen on the western side of the Paparoa Ranges and is very similar to the Morrissey Creek Section (figure 4.2). For this reason the BCM on the eastern side of the Paparoa Ranges are considered the equivalent of the exposures on the western (coastal) side. Age by macro- fossils from Wellman et al. (1981) places the BCM here as mid to Late Eocene in age

(Kaiatan Stage), again similar to the age of equivalent strata on the coastal side of the Paparoa Ranges.

### **4.3. Key localities from previous researchers**

The following section outlines some important details from other outcrops within the greater Charleston region that were unable to be visited during this MSc research. Some of the details they contain are necessary for later palaeogeographic reconstructions and interpretation so they are included mainly for this purpose. While these are the works of previous authors, my own interpretations have been added where appropriate.

#### *4.3.1. Charleston*

The area around Charleston Township has been the focus of extensive coal mining during the late 19<sup>th</sup> and early 20<sup>th</sup> centuries and obtaining original data from the area was an initial goal of field research. Unfortunately however a section complete enough to be measured was not found, hence the information on the BCM in the immediate vicinity of Charleston is solely the work of previous authors (Nathan, 1972 & 1975; Wellman et al., 1981). The information on the coals and BCM around Charleston come mainly from the many small open pit mines that operated in the Darkies Terrace area, which nowadays is overgrown land just to the east of the township.

Based on information from Simon Nathan's N.Z. Geological Survey Report on the Coal Resources of the Charleston Area (Nathan, 1972) there is a local thickening of the BCM about Darkies Terrace. Up to 76m of quartzose, poorly sorted, coarse sandstone occurs above a highly weathered gneiss (Nathan, 1975). The thickness of the weathered horizon is not stated. Generally, present within 5-10m of the base of the unit an anomalously thick low ash, high sulfur coal seam of up to 12m thickness which thins rapidly to the south. The top of the Brunner Coal Measures grades into the marine Little Totara Sand and further up section into the limestones of the Nile Group (Nathan, 1975). The sandstones of the BCM are interpreted by Nathan (1972) as meandering stream type facies with the thick coals forming on the floodplain. From the other coals in the region I suggest that the low ash (Nathan, 1972) coals at Darkies Terrace were also likely deposited within a raised peat mire. The high sulfur content can be attributed to the marine incursion that followed (e.g. Phillips et al., 1994), something

recognized in other occurrences of the BCM (Flores & Sykes, 1996; Nathan, 1996). The local thickening around the Charleston area is attributed to the topography of a valley that existed prior to the deposition of the BCM (Nathan, 1972). No mention or evidence for faulting is noted by any previous authors.

To the north of Charleston just across the Nile River the Charleston-1 drill hole intersected no coal, the bottom of the hole returning only a brown calcareous mud (which I have interpreted as Kaiata Formation) before penetrating the gneissic basement of the Charleston Metamorphic Group (Nathan, 1975; Wellman et al., 1981). In this area, BCM were either not deposited or else were eroded from a shore platform during transgression. This places a northern limit on the extent of the BCM in Charleston area and not until Tauranga Bay in the north are they again present.

Dating of the BCM in the Little Totara River, 3km north of Charleston yielded a Bortonian to Kaiatan age (upper Middle Eocene) (Wellman et al., 1981). By inference, the BCM at Darkies Terrace are likely a similar age.

#### *4.3.2. Addisons Flat*

The Addisons Flat borehole was drilled approximately 6km south of Westport. This was an exploratory borehole drilled by Solid Energy in 2005 to investigate the area to the west of the Lower Buller Fault. No BCM or indeed Kaiata Formation were intersected in the hole. Instead, the Oligocene Waitakere Limestone of the Nile Group rests directly on gneissic basement of the Charleston Metamorphic Group. The basement below the unconformity appears mostly unweathered with rounded pebbles and one large (0.5m) boulder of gneiss suspended in the basal 2m of the limestone (Appendix 1).

Oligocene strata resting directly on basement suggests that for the early part of the Cenozoic this area was likely a topographic high (see figure 4.8 for schematic interpretation). Quartzose coal measures and muddy marine facies may have accumulated and been subsequently eroded, or potentially no deposition occurred until the limestone was deposited. In either case the presence of a high at some time is needed to account for the stratigraphy observed. The large gneissic boulder also is evidence of the possibility of significant topographic relief. As the boulder is suspended within the limestone, seemingly with no other related debris, it must have been emplaced during deposition. Gravitational transport (sliding or potentially falling) as a

singular block from a scarp or localized area of high relief seems likely. Deformation of the underlying strata may have occurred but the core is poorly preserved directly below the boulder so the evidence for this may be lost.

It is important to note the proximity of Addisons Flat to the Lower Buller Fault just to the east. This fault, as the southern equivalent of the Kongahu Fault to the north, is known to have been active during the mid-late Eocene and together they controlled the subsidence and inversion of the Buller Coalfield Basin (Kamp et al., 1996). The inferred high and potential scarp eluded to above would very likely be related to this structure.

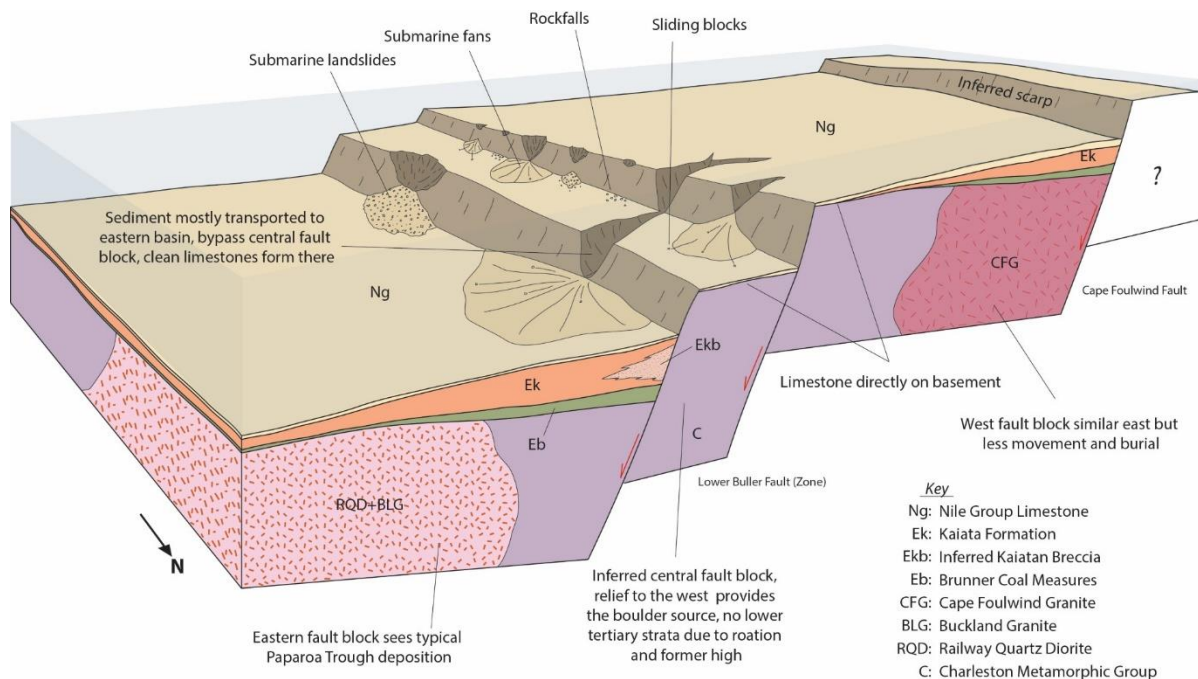


Figure 4.8: Schematic model for formation of Addisons Flat stratigraphy. The BCM are not present across the faulted uplifted high due to either tilting during deposition or erosion prior to formation of the limestones.

#### 4.3.3. Pororari River to Lawson Creek

The Pororari River and Lawson Creek sections, the two most southerly of the BCM in the Punakaiki-Charleston region, were not visited due to the difficult access and limited time constraints. Instead, map sheet S37 of Punakaiki (Laird et al., 1988) and stratigraphic columns from an N.Z.G.S. report by Harold Wellman and others (Wellman et al., 1981) were used to estimate the distribution and thickness of the strata in this area. In this region the BCM are thin and are found in a fault-bounded block.

The Pororari River column by Harold Wellman (in Wellman et al., 1981) shows a thin section with around 65ft (20m) of quartz grit above a 3ft (90cm) seam of coal sitting directly on Greenland Group basement. Unfortunately, no data or even a mention of leaching in the basement lithology is included but it is assumed that some degradation of the underlying rock will have occurred.

The Lawson Creek Column, also by Wellman (et al., 1981), has no more than 100ft (30m) of a hard sandstone with large fossiliferous concretions resting on a sub-bituminous coal seam with a thin quartz grit at base. The BCM here are restricted to the coal seam and the thin quartz grit below, as the sandstone above is marine and is likely the Little Totara Sand or Island Sandstone. Overall the coal measures are no more than 15m thick and dated by macro- and microfossils as probable Middle to Late Eocene (Bortonian to Kaiatan stage) (Wellman et al., 1981). Below the unconformity the Greenland Group basement is said to be leached in the upper part, however exact thicknesses are not stated.

It is interesting to note that in another section from Punakaiki south towards Lawson Creek apparently a trough cross bedded sandstone (presumably the Little Totara Sand or Island Sandstone) rests directly on basement (Wellman et al., 1981). It is specifically stated that no coal or coal measures are present at this locality. Where exactly this section was measured is unknown but it seems that around the coastal area of Punakaiki the base of the Cenozoic on lapping sequence may have been marine, rather than terrestrial like elsewhere.

#### *4.3.4. Giles Creek Unconformity*

Another area included purely for the sake of palaeogeographic reconstruction was a notable unconformity in the vicinity of Giles Creek. This is on the east side of the Paparoa Ranges approximately 7km south from where the section of Fletcher Creek was measured. The unconformity deserves attention as leached calcareous arkosic sandstone with granite cobbles near the base rests directly on fresh, un-weathered granite basement (Suggate, 1957; Wellman et al., 1981). The sedimentary rocks are assumed to be very Late Eocene (Runangan) Te Wharau Sands and marine in origin. This sharp unconformity with no appreciable weathering profile and the lack of earlier Eocene strata is interpreted as probable erosion about a palaeogeographic high.

#### **4.4. Regional Interpretation**

Simon Nathan (1975) described the depositional environment of the Brunner Coal Measures in the Charleston region as terrestrial, with meandering streams and peat swamps on a slowly subsiding surface of low relief. Nothing I have found during the course of research has contradicted this statement and the above interpretation holds true. Many details of the earliest deposition of the Brunner Coal Measures in this area however are important for later discussion and so will be elaborated on.

The weathering profile on the basement unconformity is generally very well developed and extends to over 15m depth in many locations. Around Charleston and further south, basement consists of gneiss, or less frequently mylonite. Weathering into these rocks typically has altered unstable minerals into clays with generally only quartz fragments left behind. The homogeneity of the rocks has resulted in a gradual weathering front decreasing in intensity with distance from the surface. At Cape Foulwind, where the weathering profile is developed into a granite, the weathering front preferentially extends from joints already present in the rock. This has the effect of producing corestones. Despite the different styles of weathering in the differing rock types, the total thickness of the weathered profile is comparable across the region.

A common feature of the weathered horizon across the region is an intensely weathered regolith directly below the unconformity. Typically this layer extends down no more than 1m and, with the exception of quartz grains, is composed entirely of clays. It is often preserved but in some cases has been scoured and eroded by the overlying fluvial BCM with complete removal in a few examples.

The importance of this layer is the indication that weathering in the Charleston region was predominantly subaerial. The erosional nature of the unconformity does not affect the geometry of the weathering front but merely truncates it. This suggests that the weathering profile was developed prior to deposition of the BCM and any leaching post deposition had a minimal effect.

Relief on this subaerially weathered surface is also apparent. The local thickening of the BCM at Darkies Terrace is attributed to preexisting topography by Nathan (1972; 1975). The absence of BCM in drill holes to the north of Charleston until an exposure at Tauranga Bay may also be the result of a topographic high. On a smaller scale, the road outcrop in figure 4.3 clearly shows that the pre-Cenozoic surface was not completely flat and that the degree of slope on the undulating surface can be quite significant.

In most locations the weathered basement and undulating unconformity are overlain by Middle Eocene (Bortonian-Kaiatan) Brunner Coal Measures. A layer of quartzose, poorly sorted, coarse sandstone is typically the first unit found at the base of the BCM. In the Fox River, Morrisey Creek and Cape Foulwind sections this sandstone is interpreted to represent fluvial channels. Based on the lenticular shape and grain size these channels are inferred to belong to meandering rivers. The upper portion of the sandstones typically fine and contain organic fragments increasing in frequency up section. These represent plant matter being deposited as part of the channel fill and probably in lower energy, oxbow lake environments formed after channel abandonment.

Up section from the basal sandstone layer is a coal seam that is common in all but one exposure of the BCM in the region (the exception being Cape Foulwind). This coal seam, where present, varies in thickness from 2m up to 12m. The coal is of low rank due to lack of burial, high in sulfur, but generally with a relatively low ash content (Nathan, 1972). The high sulfur content is attributed to the marine incursion that followed deposition of the coal measures, something in common with both the Buller and Greymouth regions (Norgate, 1997; Nunweek, 2001). The low ash content suggests that the coals formed with little detrital influx from nearby rivers and their thickness requires a significant period with no disturbance. The model of a raised peat mire (Esterle & Ferm, 1994) explains the occurrence of clean coal directly above and likely adjacent to the meandering streams recognized.

Above the coal generally a depositional environment with a marine influence is indicated, suggesting deposition on a low lying coastal plain and proximity to the coast. The transitional facies that follow can be difficult to classify as marine or terrestrial but eventually a complete marine setting is reached with deposition of the Little Totara Sand or Kaiata Formation ensuing. The transitional facies are placed within the BCM, only true marine facies are reserved for the Kaiata and Little Totara Sand.

To complicate this generalized regional interpretation, BCM do not occur everywhere in the Charleston Region. The area to the north of the Nile River all the way up to Tauranga Bay, including Addisons flat, is devoid of quartzose coal measures (figure 4.8). Similarly, the BCM pinches out to the south and supposedly does not occur at Meybille Bay or Punakaiki (Wellman et al., 1981). These areas are either representative of a) a palaeogeographic high, or b) subsequent erosion and removal of the BCM in the mid to Late Eocene. The possibility of

either scenario is considered plausible and only the lack of lower Cenozoic strata has been used for interpretations.

#### *4.4.1. Depositional History*

From the above observations a common history for the Charleston region can be deduced. Prior to deposition of the BCM the landscape was relatively flat. Minor relief on the order of 10's of meters is attributed to fluvial erosion of palaeovalleys with no evidence for faulting seen. The surface of the landscape, typically composed of gneiss or granite, is variably altered and the upper 10-15m is often very clay rich. This is attributed to prolonged chemical weathering in a subaerial soil horizon. Basement immediately below the surface is reduced to residual quartz and the rest of the parent rock has been altered to clays. Weathering of this nature is typically found in tropical climates (Martini & Chesworth, 1992; Elias & Mock, 2013) thus this period is inferred to have a similar or warmer climate than modern day North Westland.

The subsequent deposition of the BCM is interpreted as the result of gradual subsidence and marine transgression. Quartz rich residuum, derived from the highly weathered basement rocks, was eroded from the surrounding landscape and deposited in meandering streams and floodplains in a low gradient coastal plain. Migration and abandonment of stream channels was succeeded by accumulation of organic matter and the eventual formation of peat mires on the floodplains. The raised nature of these mires prevented avulsion of proximal streams and allowed thick, low ash peat to accumulate for a period of time.

Continued subsidence resulted in a wide spread marine incursion. Gradual drowning of the landscape halted peat formation and facies associated with a near coastal setting typically overlie the coals. As the sea transgressed further inland the top of the BCM became more transitional, up to the point where the strata is characteristically marine (either Little Totara Sand or Kaiata Formation). The generally thin (20m) BCM and the marine sedimentation closely following final accumulation of peat mires suggests that deposition in the Charleston region was likely directly attributed to the marine incursion.



#### **4.5. Conclusion**

Unlike the Greymouth and Buller regions, the Charleston region is interpreted to be devoid of fault control and accumulation was instead the result of a diachronous, back stepping coastal plain that deposited a thin layer of terrestrial strata prior to marine transgression. The region is characterised by extremely weathered basement suggesting a prolonged period of sub aerial chemical weathering prior to deposition in the Early Cenozoic. Palaeohighs related to later faulting, like what is interpreted to have occurred at Addisons flat, may have been active during deposition of the BCM, but this is not known. All the current evidence suggests that the region was a low lying landscape with minor relief that began slowly subsiding during the mid to Late Eocene.

## Chapter 5 Discussion

### 5.1. Summary of results

#### 5.1.1. *Late Palaeocene-Middle Eocene Weathering Profile*

A prominent leached horizon in the rocks below the Cenozoic strata is interpreted as a deep weathering profile. This weathered layer is recognized in all three of the regions of the study area (Greymouth, Buller and Chareleston) and developed into various basement rocks including Greenland Group metasandstones and argillites, Karamea and Rahu Suite Granites, Charleston Metamorphic Group gneisses and mylonites and in one instance, the mid Cretaceous – Palaeocene Paparoa Group. Generally this weathering profile is between 5-15m thick, the basement rock becoming more altered toward the overlying unconformity. In many cases the upper c. 1m is completely weathered to clays with remnant unaltered quartz grains scattered throughout.

The weathering profile is interpreted to be the result of substantial and prolonged sub-aerial weathering during the Late Palaeocene up to the Middle Eocene, prior to deposition of the BCM. The unconformity at the base of the BCM is often recognized as truncating the upper completely weathered clay layer thus must post date its formation. The weathering profile is inferred to have developed in a deep soil horizon in the warmer and wetter climate that was present in the Late Cretaceous to Eocene (Pocknall, 1990; Pancost et al., 2013). This was enhanced by the deposition of peat bogs where acidic waters caused further alteration (e.g. Martini & Chesworth, 1992) such as at Coalbrookdale.

#### 5.1.2. *Regional Transgressive Sequence*

Sedimentology of the Brunner Coal Measures has highlighted the diachronous nature of deposition. This is in accordance with the classification of the BCM as the basal unit of a regional transgressive sequence (Lever, 1999; Mortimer et al., 2014). The sedimentology and stratigraphy of the BCM shows that initial fluvial sedimentation, restricted to the central confines of older basins, is progressively overlain by lower energy, near coast facies and ultimately capped with marine sediments as the sea transgressed inland. This is observed in individual measured sections from outcrops throughout the study area and on a regional scale.

The time transgressive nature of deposition is recognized in all occurrences of the BCM. The unconformity at the top of the Palaeocene 'Brunner like' Ikes Peak Formation of the Paparoa Group and the overlying Palaeocene Island Sandstone represents the earliest indication of transgression. This is followed by deposition of the BCM on a regional scale, initially confined to basins (e.g. Buller Basin) but with terrestrial sedimentation later progressing through most of north Westland throughout the Middle Eocene (Bortonian) period.

The marine transition, while not always present in outcrop, is the defining feature that separates the BCM from the later Cenozoic strata. Marine sediments are in all cases eventually deposited above the BCM but the timing of the marine incursion, like the initiation of fluvial deposition, is diachronous. The Middle Eocene, about the time of the Bortonian – Kaiatan stages (42.6 – 39.1 Ma), saw the period in which the majority of transgression occurred. Specific locations however were invaded by the sea much earlier (Mid Eocene in the Greymouth Basin), and in other areas much later (Late Eocene at Cape Foulwind). These variations are most often attributed to the geography of the landscape and in some cases, minor faulting.

#### *5.1.3. Topographic Relief and Faulting*

There are notable occurrences of both minor faulting and inherited topography in the Early Cenozoic landscape. Work of previous authors (Titheridge, 1993; Flores & Sykes, 1996) and data obtained during this research have provided evidence for both local topography and syndepositional faulting in the earliest Brunner Coal Measures. These features have had varying levels of effect on deposition, which in some cases may explain the anomalies in the diachronous regional transgression.

Where present and not related to syn- or post-depositional faulting, topography on the basal unconformity is noticeable. Ranging from a few to tens of meters in height (Flores & Sykes, 1996) this relief is a feature that developed in the period prior to wide spread deposition in the Middle Eocene. The mechanism of formation is envisaged as small tributary streams slowly down cutting into the landscape and forming the highs and lows of valleys and ridges. Thin localized polymict basal conglomerates scattered throughout the Buller Coalfield represent these streams situated in topographic lows. Outside of the Buller Coal Field generally only the on lapping relationship of sedimentary strata on the basement unconformity indicates that topography was present. Conglomerate lag has not been recognized in any great quantity

outside of the Buller Region, but such deposits are likely to be found in the bottom of valleys and depressions based on the examples there.

Minor faulting of the BCM has at present only been recognized in the north within the Buller Coalfield. Titheridge (1993) undertook a comprehensive investigation focused on syndepositional tilting of the BCM and found that NNE and NW trending faults influenced both thicknesses and seam splits.

Older syndepositional faulting in the Palaeocene has also been encountered during research. In the Greymouth basin NNE trending fault(s) controlled deposition of the Hall Ridge Conglomerate Member in the newly defined Ikes Peak Formation of the Paparoa Group. In the Buller Region the Papahaua Formation (also of the Paparoa Group) in the Mt. Rochfort half graben indicates fault control with a NW orientation.

Faulting has influenced deposition and topography across the study area. From the earliest Cenozoic deposits to well into the Eocene (Kaiatan stage and later), North Westland has experienced significant syn-tectonic deposition. This greatly influenced the landscape and the distribution of the lower Cenozoic strata and can be used to explore the probable tectonic evolution during this time.

## **5.2. Palaeogeographic Reconstructions**

Palaeogeographic maps for the Late Palaeocene-Middle Eocene have been constructed from the information gathered during field work combined with existing literature. To my knowledge there are currently no detailed palaeogeographic reconstructions of this period for coastal North Westland and with a focus on regional landscape evolution.

Dating by macro- or microfossils was not a part of this research, instead the chronology essential for a palaeogeographic reconstruction is based on previous literature (Couper, 1960; Wellman, 1981; Raine, 1982; Newman, 1985; FRED). Some of the data available was questionable and at times several stages were indicated for the BCM alone. Therefore much of the reconstruction was based on interpretations of the stratigraphy with the probable transition of depositional settings being inferred from this. These reconstructions, while containing some uncertainties, document the probable sequence of deposition from the Palaeocene through to the Middle Eocene.

### *5.2.1. Early Eocene (Mangaorapan stage c. 50 Ma) - Birchfield Sandstone/Unconformity*

Beginning in the earliest Eocene, the majority of the costal North Westland region was undergoing prolonged subaerial weathering (figure 5.1). This is indicated by development of a significant leached horizon and production of an unconsolidated quartzose residuum (see previous chapters 2, 3 and 4). Small streams down cut into the leached basement forming shallow valleys and an overall landscape of minor undulating relief. Local basal conglomerates, often found in the Buller Region, occupy depressions in the topography of the leached surface and are probably remnants of this time (Titheridge, 1993).

The Greymouth Basin, discussed extensively in chapter 3, represents the only definite occurrence of faulting present during this period. As was previously established, the Greymouth Basin experienced a late stage tectonic episode during the end of the Palaeocene in which an eastern basin bounding fault became active (approximately correlating with the modern day Roa-Mt Buckley fault zone). This fault and the associated uplift to the east, removed any Late Cretaceous to Early Palaeocene Paparoa Group strata that may have been present there and resulted in deposition of the Ikes Peak Formation. Sedimentation slowed following this and approached a period of non-deposition at the top of the Birchfield Sandstone, which is shown for this time in figure 5.1. The eastern basin bounding fault that controlled deposition of the Ikes Peak Formation was likely dormant, or becoming that way at this time. Low energy fluvial systems are interpreted to be present in the center of the basin but have little impact on the accumulation of long lived peat mires (Newman, 1985).

At Pike River, roughly 20km north, an influx of coarse grained sediment is not recognized for the same time period and the zone of uplift and the eastern fault is therefore inferred to be localized to the Greymouth Coalfield only. No major unconformity is recognized at Pike though (Raine, 1984), so continued deposition through this time is a possibility. Newman (1985) states that dating of the high rank Pike River coals is poor and therefore such an unconformity may exist. The area has currently been left blank to highlight this uncertainty.

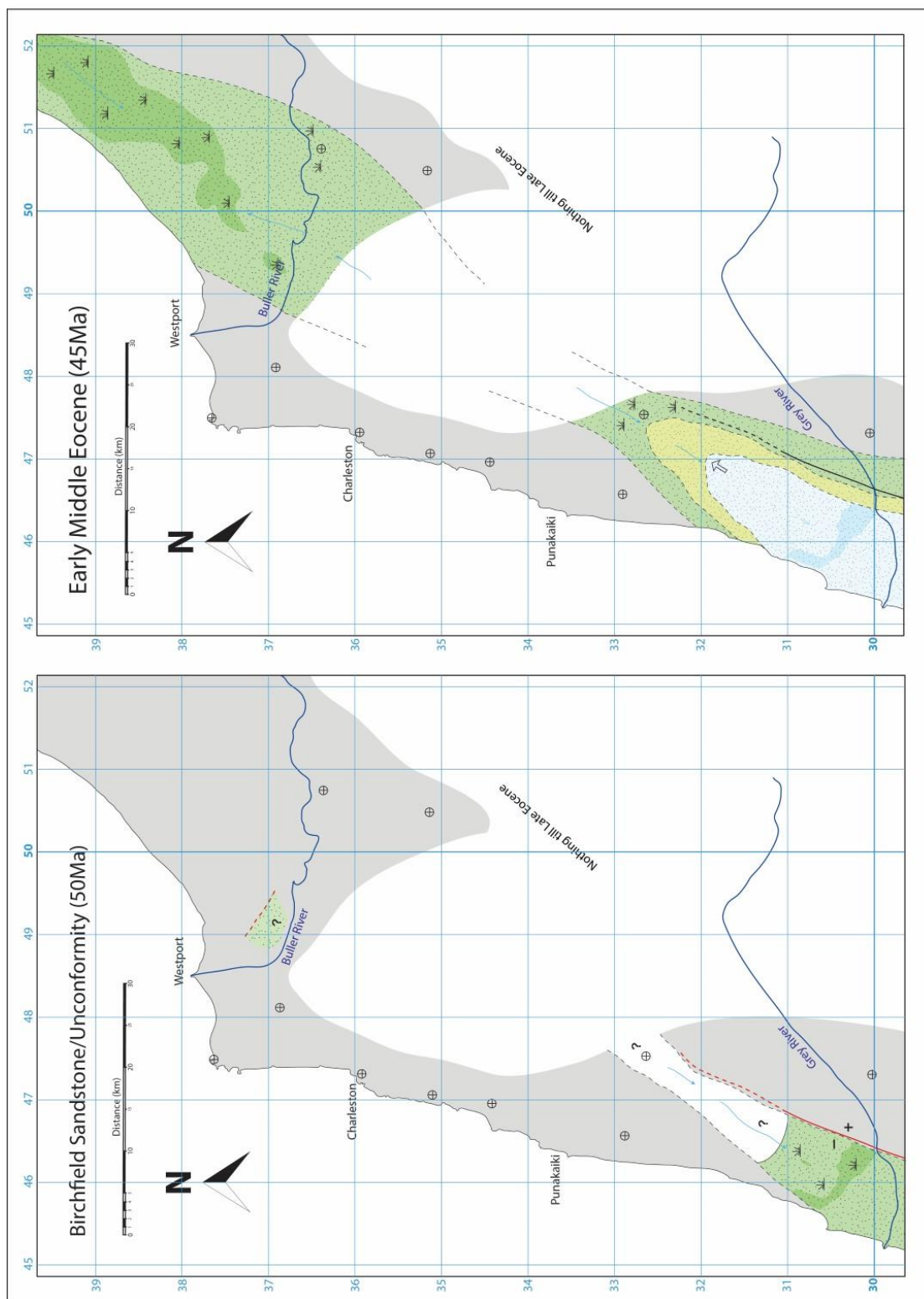


Figure 5.1: Palaeogeographic reconstruction of coastal North Westland for the Early Eocene (50 Ma) and the early Middle Eocene (45 Ma) (Mangaorapan and Porangan stages respectively).

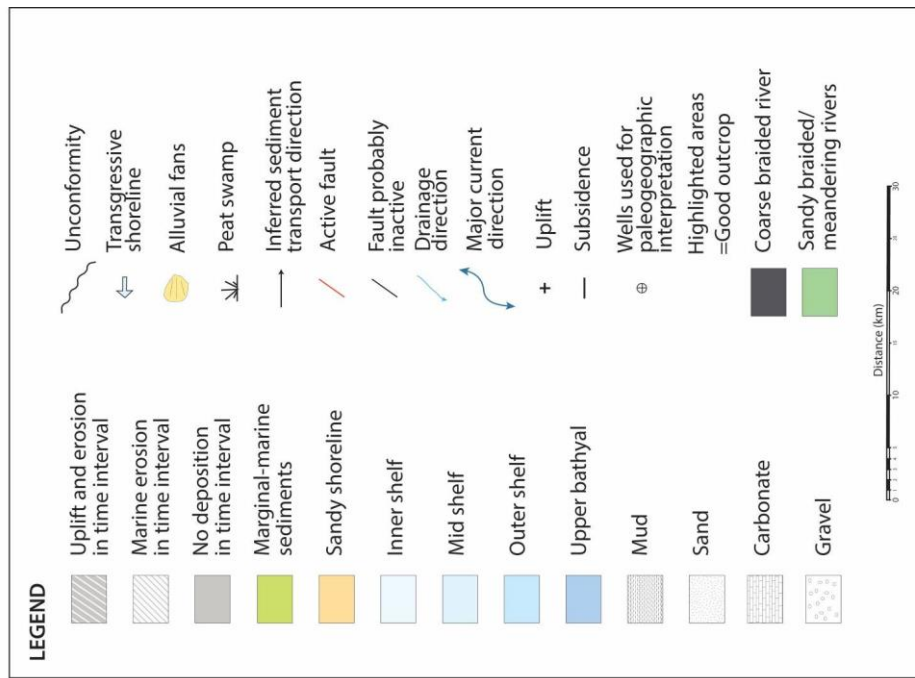


Figure 5.2: Key for Palaeogeography Maps (palaeogeographic symbology modified from Tripathi et al., 2014)

In the far North at Te Kuha, the newly recognized Papahaua Formation may represent a similar situation. No obvious break is seen in the stratigraphy between the Papahaua Formation and BCM except for a slight angular unconformity in the most northeastern outcrops. Potentially part, or all of the section could be a northern equivalent of the Ikes Peak Formation or correlative with other Paparoa Group formations. The Papahaua Formation is therefore tentatively drawn for this time.

### 5.2.2. Early Middle Eocene (Porangan stage c. 45 Ma) - BCM and Island Sandstone

Meandering rivers and floodplains truncate and overlie the leached basement in the Buller Basin (figure 5.1). The sandy deposits are very quartzose and are derived from the quartzose residuum that had been forming in the period prior (Suggate, 1950; Nathan and McKenzie, 1986). The coal measures initially fill and overtop the inherited topography of the highly leached basement and the landscape within the basin quickly becomes quite flat. Raised peat mires, once established, persisted for significant periods and accumulated thick coals on the low gradient floodplains.

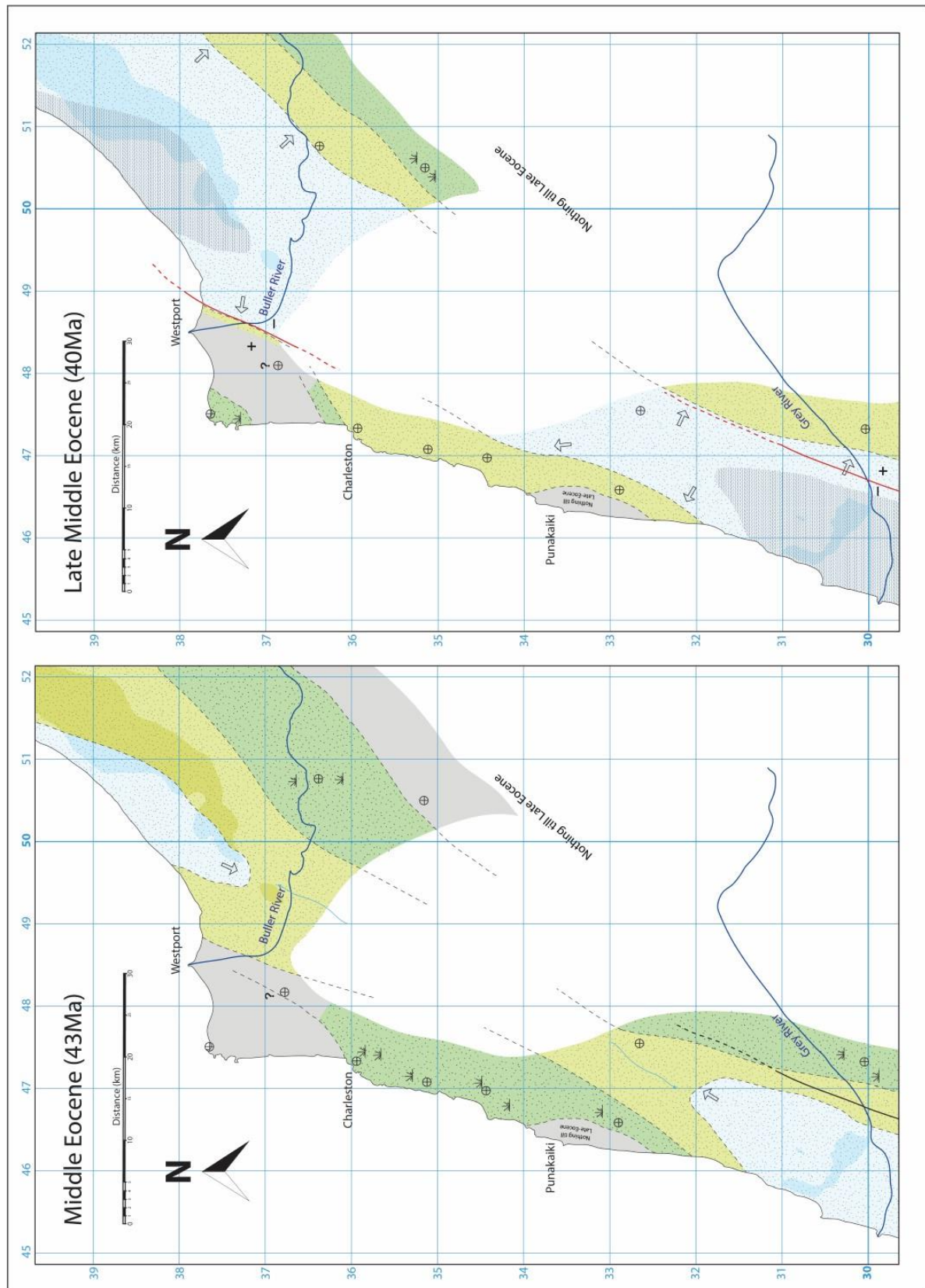


Figure 5.3: Palaeogeographic reconstruction of coastal North Westland (Porangan-Bortonian and Bortonian-Kaiatan stages)



In the Greymouth Basin to the south the time equivalent of the BCM is the near shore marine Island Sandstone. The basin was flooded during the earliest Middle Eocene (Porangan) and yellowy fine glauconitic sandstones with infrequent coal lenses at the base directly overlie the fluvial quartzose sands and coal of the Birchfield Sandstone Member (Newman, 1985; Nunweek, 2001).

To the north of the Greymouth Coal Field the quartzose coarse sandstones of BCM had begun deposition in the Pike River Coal Field. Unlike the Buller Basin in the north, the BCM at Pike River are thin (<5m) (Newman, 1985) and likely represent a near coast environment being overlain by marginal marine facies before transitioning to fully marine. For this reason these marginal marine facies and the inland fluvial meandering streams, rivers and mires of the BCM are inferred be representative of a transgressive shoreline and coastal plain. This shoreline had likely been extant since the initial flooding of the Greymouth Basin and transgressed northwards as the basin continued to subside.

Between the Pike River Coal Field and the Buller Basin, Cenozoic strata is no longer exposed so interpretations through this area are speculative only. Based on the areas seen to the north and south though, it seems that a low lying plain existed roughly along the trend of the modern day Paparoa Range. Based on palaeoflow data (Flores & Sykes, 1996) this plain likely drained north into the Buller Basin and from cathodoluminescence data (Bassett et al., 2006), also south through the Pike River Coal Field towards Greymouth. This area may have acted as a sediment bypass or possibly as a source for some of the quartzose sandstones deposited in the basins.

Outside of the Greymouth and Buller Basins, and the low lying plain in-between, the landscape continued to undergo a period of non-deposition with the leached soil horizon further developing.

### *5.2.3. Middle Eocene (Porangan – Bartonian stages c. 43 Ma) – BCM widening*

The nature of deposition during the Middle Eocene period is characterised by a general stepping out of the basin areas (figure 5.3). In the Buller Basin in the north the majority of the area is heading toward a near coast setting with deltas, estuaries and tide influenced sedimentation common. Age control on the transition to a marine setting is poor and variable (Flores & Sykes, 1996), but the sea may have already started to transgress by this time, presumably along the depocenter of the basin where estuarine deposits are the thickest.

In the south, the marine embayment that flooded the Greymouth Basin progressed further inland, predominantly in a northerly direction. Above the thin BCM at Pike River there is a transition to the Kaiata Formation through a succession of delta, shore face and eventually shallow marine facies. This suggests a slow, gradual transgression of the sea from the south. To the east of the Greymouth Coal Field in the Blackball area, Middle Eocene (Bortonian stage) fluvial BCM (Couper, 1960) were deposited directly above leached Greenland Group basement, representing the subaerial high at the edge of the basin. The marine embayment was likely also transgressing eastward then since the deposits are from very low gradient meandering rivers, indicating stepping out of the Greymouth Basin. This stepping out is inferred to have been somewhat slower than the northward transgression.

Deposition of the BCM in the Charleston Coal Field had commenced (Nathan, 1975; Wellman, 1981; Laird, 1988). Through extrapolation it is inferred that the rest of the Charleston-Punakaiki region (with the exception of Cape Foulwind) was also undergoing the initial stage of deposition. Field investigations highlighted that terrestrial sedimentation throughout the region is variable, often with marine facies sitting directly on basement. This suggests a highly complex coastline with multiple embayments and headlands so deposition of the BCM and later flooding is probably much more complex than is shown.

#### *5.2.4. Latest Middle Eocene (Bortonian – Kaiatan transition c. 40 Ma) – BCM to Kaiata Formation*

By the latest Middle Eocene the Greymouth and Buller Basins were completely invaded by the transgressing sea and the connecting plain between the two is inferred to have also been likely flooded at this time (figure 5.2).

On the east flank, the shoreline continues to step inland. Marginal marine facies are present in the No Town bore (Wellman et al., 1981) to the east of Blackball thus the coast is inferred to be slowly migrating to the east. Based on chronology from Wellman et al. (1981), the BCM at Fletcher Creek on the east side of the Paparoa Ranges also began depositing at this time. Characterised by fluvial meandering rivers, oxbow depressions and peat mires, sedimentation here is interpreted to represent the continued eastward stepping out of the Buller Basin but lagging slightly behind the transgression in the south.

In the Charleston-Punakaiki region, estuary, delta and shore face deposits are common. It is inferred that the sea transgressed in a westerly direction, in a similar stepping back fashion of the coast line like on the eastern flank. To the north though, around the Addison's Flat bore, limestone of the Oligocene Nile Group rests directly on a gneissic/mylonitic basement with no coal measures present (Appendix 1). In terms of palaeogeography, this could represent a basement high in which deposition did not occur on until a very late stage of drowning. However it could also reflect a period of erosion subsequent to deposition of the BCM. In either scenario there was no early Cenozoic strata preserved here.

Just west of Addison's Flat at Cape Foulwind a thin occurrence of BCM is dated as Kaiatan (Nathan, 1976). This suggests that deposition here was somewhat separated from the BCM to the south, and certainly from deposition in the Buller Basin. The high at Addisons Flat is therefore interpreted as a result of faulting along the proto-Kongahu Fault Zone which is also inferred to have become active at this time. The small separated basin at Cape Foulwind likely represents the tilting of the eastern footwall fault block and creation of a localized basin down dip to the west.

The eastern basin bounding fault in the Greymouth Basin may also have become active again during this period. Approximately coinciding with the Roa-Mt Buckley Fault Zone this fault is known to have controlled deposition of the Kaiata Formation (Nathan, 1978). As marine deposition had commenced by this stage, this fault was likely initiated at, or very shortly after this time.

A Late Eocene (Kaiatan stage or younger) palaeogeography map covering the end of transgression was not constructed due to being beyond the scope of this thesis. However, North Westland and the remainder of Zealandia entered an ever increasingly drowned stage throughout the Eocene and Oligocene (Kamp, 1986b). Not long after the final reconstruction there would be a total submergence of the study area with transgression being complete. For interests sake though, Lever's (1999) palaeogeographic reconstructions for North Westland begin in the Kaiatan. These can be used to further illustrate the geographic and facies evolution of the region into the Late Oligocene.

**Tectono-sedimentary Model for the Late Eocene  
(Bortonian-Kaaitan), Coastal North Westland**  
Equates to Gawthorpe & Leeder's (2000) model of initiation in a coastal environment

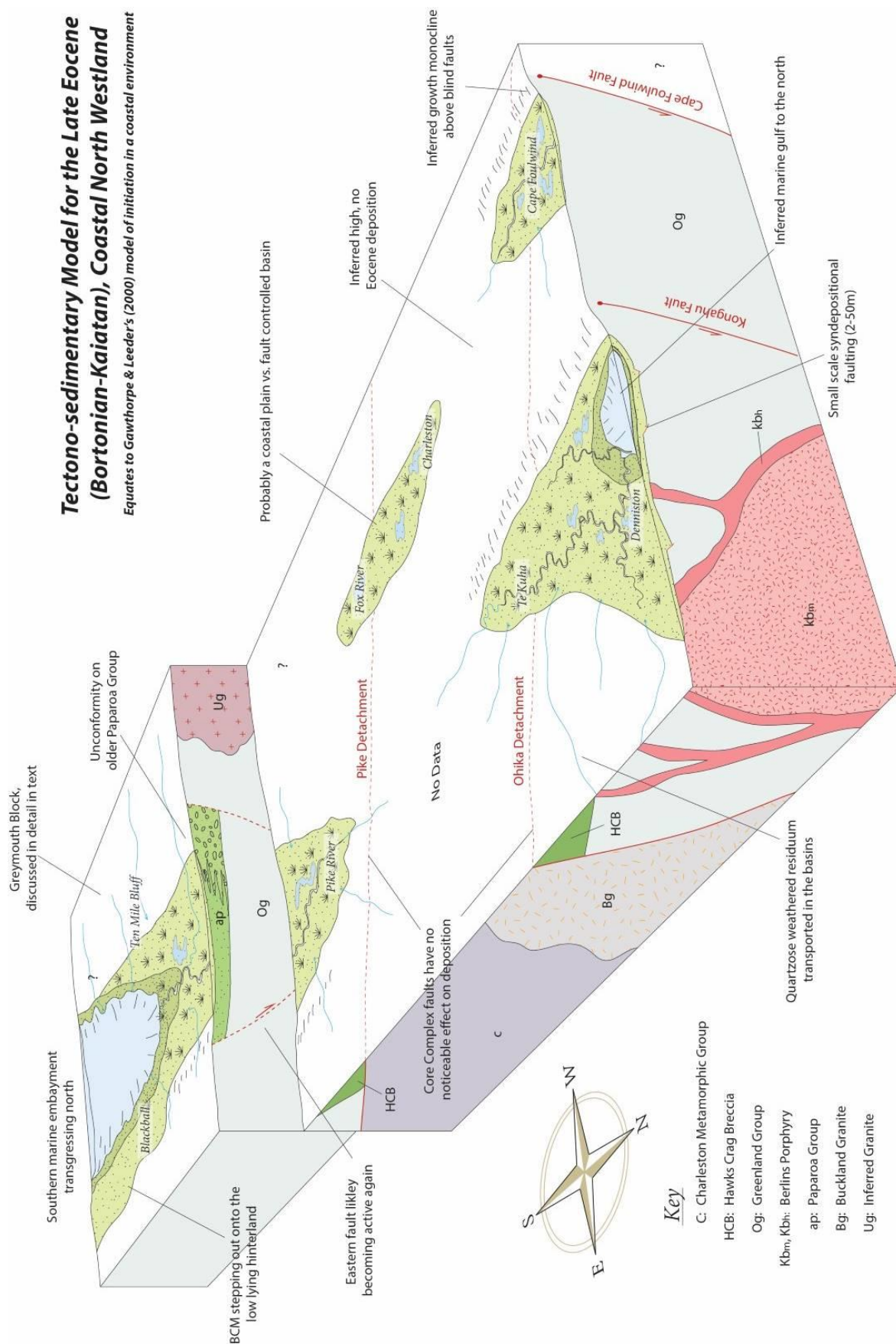


Figure 5.4: Tectono-sedimentary model for Coastal North Westland (entire study area)

### **5.3. Coastal North Westland Bortonian- Kaiatan Tectono-Sedimentary Model**

With the interpreted Late Palaeocene to Middle Eocene palaeogeography of coastal North Westland and the detailed stratigraphy of much of the study area well documented, a regional tectono-sedimentary history can be deduced. The Middle Eocene (entirety of the Bortonian and beginning Kaiatan stage) covers the majority of deposition of the BCM and the model was drawn to reflect this time. The model (Figure 5.4), was mostly constructed with the information on stratigraphy outlined in chapters 3-5 and the resultant palaeogeographic reconstructions for this time (Figure 5.3).

#### *5.3.1. Overview*

The model (figure 5.4) depicts a landscape of low relief influenced by multiple disconnected normal faults with small offsets. These faults control the location of the initial basins but do not have an obvious expression in the sedimentary record.

The two fault orientations incorporated into the model are the NNE trending structures present during the Late Eocene (Kamp, 1986a) and the NW trending mid Cretaceous core complex detachment faults. These two fault sets represent the major structural controls that may have been active during the deposition of the Brunner Coal Measures (Newman, 1985; Ward, 1997; Riordan et al., 2014), so were included on that basis. Based on the palaeogeographic reconstructions of the previous section it was clear that the NNE trending structures had influenced deposition so the model is drawn to reflect this.

An apparent association of deposition to the north and south of the core complex shown in the model (figure 5.4) could possibly be misinterpreted as evidence for reactivation and influence from detachment faults. While the distribution of basins on the down thrown side of detachment faults may be the case, the intervening area, some 45km between Pike River and Te Kuha, is completely devoid of outcrop. Interpretation through this area is therefore left as a question mark and any relationship to the core complex faults is not intended.

The southern portion of the model is based on the basin evolution introduced in the discussion of the Greymouth region (chapter 3). A marine embayment associated with transgression during the Middle Eocene is progressing northwards and gradually stepping out beyond the confines of the previous Greymouth Basin (extent of the Paparoa Group).

In the north, two separated basins (Cape Foulwind and Buller) are experiencing the initial stages of terrestrial sedimentation and the beginning of marine transgression respectively. The BCM in the Buller Basin are influenced by small scale syndepositional faulting and are far thicker than the BCM at Cape Foulwind. The marine transgression is inferred to be constrained to within the basin, likely as a marine gulf, and migrating south to eventually join with the southern embayment and flood the landscape. The areas beyond the basins are inferred to be dominated by small incising or meandering streams. These incised drainages erode and transport the quartzose residuum that formed during the Late Palaeocene and Early Eocene unconformity into the basins, resulting in the quartzose nature of the BCM.

The distribution of the BCM in the Charleston area does not allow a thorough interpretation but the sedimentary facies generally indicate deposition in a coastal plain, likely controlled primarily by the marine transgression. The lack of syndepositional faulting in the Charleston area suggests that the basin bounding faults in the Buller Basin were not major through going faults. Instead faulting at this time is interpreted to be mainly occurring on small unconnected normal faults.

In terms of comparing this model to other established models, Gawthorpe and Leeder's (2000) tectono-sedimentary evolution of an initiating normal fault array in a coastal/marine environment is very similar (Figure 5.5). While at a slightly later phase of transgression, many of the features shown in Figure 5.4 are also represented in this model. The three main features both models share in common are: sub-basins aligned with underlying tectonic lineaments, fault propagated folds where faults do not yet break the surface, and incipient hanging wall and major axial drainage patterns.

### 5.3.2. *Suitable analogues*

Real world examples of initiating coastal extensional systems are limited as most have progressed to the surface breaking fault growth stage and are dominated by marine deposition. The Suez Rift in the Gulf of Suez is one case though where extensive exploration for hydrocarbons has allowed the early depositional and tectonic history of the basin to be well constrained. The Suez Rift is situated at the very northern end of the Red Sea as the northernmost extension of the Red Sea Rift associated with the separation of the Arabian and Nubian Plates (Bellahsen et al., 2006). The Suez Rift was actively rifting from c. 25 Ma till 15.5 Ma when plate motion was likely transferred onto the sinistral strike-slip Dead Sea

Transform. Extension resulted in predominately normal faulting with formation of horst and graben fault blocks sub-parallel to the basin margins (Gawthorpe et al., 1997).

The Suez Rift in its initiation phase was characterised by isolated continental sub basins controlled by both surface and non-surface breaking faults (Gawthorpe et al., 1997). These sub basins were only present for a short time before marine transgression and the transition from continental to marine deposition occurred (Bellahsen et al., 2006). These sub basins were approximately aligned and can be correlated with faults that later became dominant structural features in the marine depositional environment. The evidence for these early subaerial basins in the sedimentary record are thin, terrestrial clastic rocks often onlapping basement and thinning toward faults or inferred growth folds (Gawthorpe et al., 1997). These features are in common with Gawthorpe and Leeder's (2000) model and also with the tectono-sedimentary model for costal North Westland (Figure 5.4)

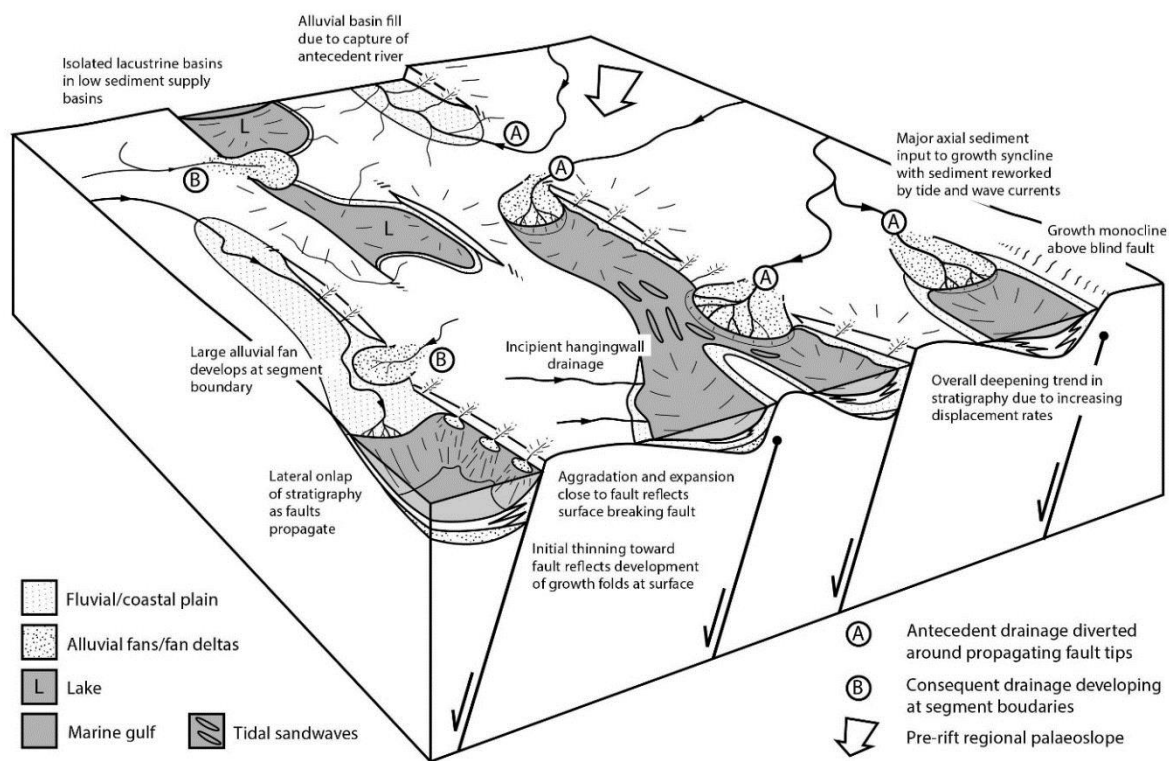


Figure 5.5: Tectono-sedimentary evolution of a normal fault array (coastal/marine environment); initiation stage. (Gawthorpe & Leeder, 2000).

### 5.3.3. *Regional Tectonic History*

#### 5.3.3.1. *Late Palaeocene - cessation of Tasman Sea spreading*

Prior to deposition of the Brunner Coal Measures the North Westland region was influenced by a different tectonic setting. Zealandia was extending at this time and drifting away from Australia and Antarctica with opening of the Tasman Sea. The Late Cretaceous-Late Palaeocene basins and the Paparoa Group within are the sedimentary expression of this extensional episode.

In the Greymouth Basin, the Late Palaeocene is interpreted as the end of this extension (Newman, 1985; Ward, 1997). A gradual decline and death of tectonic activity is what typically characterizes the end of an extensional episode (Jackson, 1999) and the stratigraphy of the Ikes Peak Formation generally conforms to this view (Chapter 3). The switch in the bounding faults from west to east during deposition of the Hall Ridge Conglomerate is therefore an unexpected change.

Fault switching is a common phenomenon and is most often associated with a change in principle stress direction and/or beginning of a new extensional regime. With a change in extension, an active fault may no longer be ideally oriented for accommodating displacement and another, more favorably oriented fault can become dominant (Nixon et al., 2014). Potentially, the west to east fault switch in the Greymouth Basin is a reflection of such a change in extension direction, prior to the cessation of tectonic influence in the latest Palaeocene.

Gaina et al. (1998) identified a late stage counterclockwise rotation of extension in the Tasman Sea Basin about chron 25y (55.9 Ma). This time approximately coincides with the initial deposition of the Ikes Peak Formation and hence the inferred west to east switch in the basin bounding fault. This rotation could therefore explain the switch, where by the eastern fault was more ideally aligned with the new extension direction and became the dominant fault accommodating the majority of displacement.

#### 5.3.3.2. *Late Palaeocene - Eocene - Tectonic Quiescence*

The eastern fault of the Greymouth Basin was short lived following its inception. By the end of the Palaeocene there is no evidence in the sedimentary record to suggest that it was active at all. The Hall Ridge Conglomerate quickly fines up into the Birchfield Sandstone and a long period of no or very little deposition occurred through to the Middle Eocene



(Porangan/Bortonian transition). Not until the Late Eocene (Kaiatan stage) during deposition of the Kaiata Mudstone does this eastern fault have any effect on deposition (Nathan et al., 2002) so was likely not reactivated until this time.

The sudden end of faulting in the east, just after the fault was initiated can again be correlated with spreading in the Tasman Sea Basin. Shortly after the rotation in extension direction occurred, spreading ceased completely. This is suggested by Gaina et al. (1998) to have happened at approximately chron 24o (52 Ma), which correlates with the end of deposition in the Greymouth Basin.

The period of non-deposition that followed is recognized across North Westland as the prominent unconformity at the base of the Brunner Coal Measures. The deep weathering profile that often typifies this unconformity is interpreted to have developed over a substantial amount of time and represents a deep soil horizon formed in a warm tropical climate (Pocknall, 1990; Pancost et al., 2013). A long period of tectonic quiescence is therefore inferred following the cessation of spreading in the Tasman Sea Basin. This persisted through the Late Palaeocene up till the Early-Middle Eocene when renewed extension and subsidence associated with the inception of the Challenger Rift resulted in the deposition of the Brunner Coal Measures.

#### 5.3.3.3. *Middle Eocene - Inception of the Challenger Rift*

Deposition of the Brunner Coal Measures is closely associated with the tectonic controls prevalent in the Late Eocene and Oligocene. Specifically the NNE oriented proto-Kongahu Fault Zone bordering the west side of the Buller Basin and the Cape Foulwind Fault Zone some way to the west of Cape Foulwind likely became (figure 5.4).

In both the Buller and Cape Foulwind Basins the bounding faults during the Middle Eocene (Bortonian) are inferred to be minor and disconnected, with only small amounts of offset occurring during deposition of the BCM. These restrict deposition to the respective basins and result in the NNE trend recognized. As extension progressed, these faults eventually did connect, breaking the surface and formed large submarine scarps in the Late Eocene (Kaiatan) continuing through into the Oligocene (Nathan, 1978b; Laird, 1988; Nathan et al., 2002).

Extension during the Late Eocene and Oligocene is common across Zealandia. This period is characterised by a time of continental rifting and creation of numerous N-S oriented rift basins in what is collectively known as the Challenger Rift System (Kamp, 1986a; 1986b; Furlong

and Kamp, 2013). The Middle Eocene (Bortonian) tectonic control on deposition is therefore interpreted as the initiation of that rifting. This also places an approximate age for the earliest inception of the Challenger Rift System in North Westland.

#### **5.4. Key issues addressed by the tectono-sedimentary model**

There are three main points that the model (figure 5.4) addresses in regard to deposition of the Brunner Coal Measures. They are:

1. The relationship to the Late Cretaceous – Palaeocene Paparoa Group in the Greymouth Region, including any influence of either the inferred eastern or western basin bounding faults.
2. The relationship to Late Eocene - Oligocene NNE trending structures of the Challenger Rift System, known to have a major influence on deposition throughout the Late Eocene (Flores & Sykes, 1996; Kamp, 1986a; Nathan, 1978b).
3. The relationship to mid Cretaceous core complex detachment faults, the exposed core complex itself and the associated half graben basin fill of the Pororari Group (Hawks Crag Breccia).

##### *5.4.1. Relationship to the Late Cretaceous-Palaeocene Paparoa Group*

In the Greymouth Region (see chapter 3 for in depth discussion) the Late Cretaceous-Palaeocene Paparoa Group was deposited in a fault bounded basin with dominant faulting to the northwest (Cody, 2015). The proposed activation of an eastern fault for the Hall Ridge Conglomerate Member of Ikes Peak Formation rather than the northwestern basin bounding fault dominant for most of the basin's history is the last major tectonic event recognized before the Late Eocene (Kaiatan stage) (Nathan et al., 2002). For the Middle Eocene no such fault control can be seen.

The Greymouth Basin was at the time of the presented model mostly marine. The Island Sandstone in the center of the coalfield is dated as Middle Eocene (Bortonian stage) (Raine, 1982), but contemporaneous with deposition of BCM to the north at Pike River (Raine, 1984; Newman, 1985). A marine embayment open to the south is interpreted from these observations (figure 5.1). To the east and west there are also Bortonian age BCM resting unconformably on

either basement or Dunollie Coal Measures. Therefore the marine embayment was relatively narrow and seemingly constrained by the extent of the Greymouth Basin.

Although no direct evidence for faulting is recognized during the Middle Eocene (Bortonian), the relationship to the Paparoa Group does show some control over deposition. This is inferred as infilling of the shallow depression that remained at the end of deposition of the Birchfield Sandstone. The Middle Eocene also saw the stepping out of the BCM beyond the basin and onto the hinterland. This is evident with deposition of the Bortonian age BCM at Blackball (Couper, 1960). This indicates that while faulting did not directly control the BCM here, regional subsidence through either long term thermal relaxation and/or thinning related to the onset of extension in the Challenger Rift initiated transgression and associated terrestrial deposition inland.

#### *5.4.2. Relationship to the Late Eocene - Oligocene Challenger Rift System*

In the north of the study area the Buller and Charleston Regions may contain the most substantial evidence for fault control during deposition. On the smaller scale, there are multiple documented occurrences of syn-depositional faulting in the BCM (Titheridge, 1993; Chapter 4). These offsets range from less than 2m to over 50m but have orientations in both NNE and NW directions. On a regional scale, while these faults show that there was some tectonic activity in the Middle Eocene, there is no indication of the probable orientation of the overall structural control.

What is apparent in the BCM thickness and sedimentary facies as shown in the model is that there are two distinctly separate basins, the Buller Basin and another small probable sub-basin at Cape Foulwind. The Buller Basin has been recognized since the earliest publications on North Westland geology (Morgan & Bartrum, 1915) but the Cape Foulwind basin is newly proposed in this thesis. The reason for a separate basin here is due to the information gained from the Addisons Flat Borehole (Appendix 1), approximately between the two (figure 1.1). The inferred high and the history of fault block tilting here (see chapter 4) does not necessitate a basin during deposition of the BCM explicitly, but certainly sometime during the Late Eocene.

With these two basins it is clear that the dominant NNE trending structures of the Late Eocene (Kaiatan stage) were also the main controls on deposition in the Middle Eocene. The Buller

Basin, while containing abundant small scale syndepositional faulting, was likely mainly controlled by the proto-Kongahu Fault (Zone) to the west. Likewise the Cape Foulwind Basin was probably controlled by the Cape Foulwind Fault not far to the west, and by rotation and tilting of a western fault block.

The remainder of the coastal region between Charleston and south of Punakaiki is left as an unknown. Sedimentary facies suggest that the region was representative of a back stepping coastal plain but the region is known to have significant eastern fault control in the Late Eocene (Lever, 1999). The current standing of information on the BCM in this region do not allow a confident conclusion to be made.

Collectively, the pattern of deposition in the Middle Eocene across the study area represents the approximate shape and extent of the Paparoa Trough (Kamp, 1986a; Nathan et al., 2002), a section of the larger Challenger Rift System. While BCM and other early Cenozoic sediments are found beyond the confines of this structure, the areas of maximum subsidence and greatest accumulation are certainly within its axis (Laird, 1968; Nathan et al., 1986; Ferguson, 1993; Lever, 1999; Riordan et al., 2013).

The Paparoa Trough itself is a difficult feature to define. During the Miocene- present day uplift, much of the trough has been removed as many of the Paleogene normal faults have been reactivated as reverse structures and inverted most of the basin(s) (Nathan & McKenzie, 1986). This lack of data is shown on the palaeogeographic reconstructions with the majority of the Paparoa Range as a total unknown. The presence of this feature is recognized mostly due to inference and the intermittently exposed lower Cenozoic succession along the coast and range front (Laird, 1968; Lever, 1999; Nathan et al., 2002).

The new evidence obtained from Addisons Flat adds to the history of the earliest Paparoa Trough in the northwest. In contrast to the previous model for an east dipping western fault block (Nathan et al., 2002) I suggest that in the Westport area, both the eastern and western fault blocks were dipping to the west (Chapter 4). This is primarily due to the lack of lower Cenozoic strata and the boulders of gneiss suspended within the limestone there necessitating a high. If the previous model was correct then Addisons flat would more likely have been a basin. As the area has been interpreted to represent a high through this time, uplift here is best explained by rotation of the west fault block, dipping to the west.

#### 5.4.3. *Reactivation of mid Cretaceous detachment faults*

Evidence for extension in the Late Cretaceous through to the Late Palaeocene is substantial. The exact orientation of this extension in the North Westland region though is still debated. Within the sedimentary basins accumulating at this time, a dominantly NNE trend has led to an inferred approximate E-W extension direction and a simple orthogonal rift system (Gage, 1952; Newman, 1985; Nathan et al., 1986; Ward, 1997). The alternative view, based on plate reconstructions (Figure 5.6), is that of a dominantly NNE trending strike slip or transtensional rift system through the Westland region (Laird, 1994).

Reactivation of mid Cretaceous structures has recently been recognized to have occurred from the Late Eocene (Kaiatan stage) and into the Oligocene (Riordan et al., 2013). Reactivation of older faults in new extensional regimes is common (Etheridge, 1986; Nixon et al., 2014) so potentially such reactivation could be seen in the BCM. The relationship between deposition of the Brunner Coal Measures, the basement Paparoa Core Complex and evidence for reactivation could have implications for the interpretation of regional extension during the Late Palaeocene to Middle Eocene (prior to the Kaiatan).

The claimed thickness of the BCM at Fox River (Wellman et al., 1981; Riordan et al., 2014) was a promising suggestion that mid Cretaceous E-W trending faults had been reactivated during the Middle Eocene (Bortonian) but investigation of the area revealed that no such thickness anomaly was present. Elsewhere, such as at Te Kuha or even Cape Foulwind, there is no apparent thickening or any noticeable influence of the Ohika Detachment on deposition of the BCM. There is however a probable relationship between the Ohika Detachment and the fault controlling subsidence in the Papahaua Formation and the Mt Rochfort Graben (chapter 4).

During the Palaeocene, the northern detachment of the Paparoa Core Complex, the Ohika Detachment (or probably a related fault) was partially reactivated. While no longer thought to be Middle Eocene in age this feature is important for interpretation of the tectonic setting during the Late Palaeocene – Early Eocene. Reactivation in an E-W extensional setting would result in approximately proportional normal to dextral oblique movement of brittle faults associated with the Ohika Detachment. In the transtensional setting of Laird (1994) an approximate NNE-SSW extension direction is inferred, roughly similar to the orientation of the identified basins. Reactivation in this setting would result in predominantly normal movement with a small amount of sinistral oblique shear.

As it currently stands, only normal movement of the Mt Rochfort Graben's inferred basin bounding fault is recognized. In a future study, if a strike slip component to the Mt Rochfort Graben was identified then the probable tectonic setting in which reactivation occurred could be resolved. The Papahaua Formation may therefore have the potential (with sufficient palynological dating) to reveal the direction of extension during the Late Palaeocene – Early Eocene.

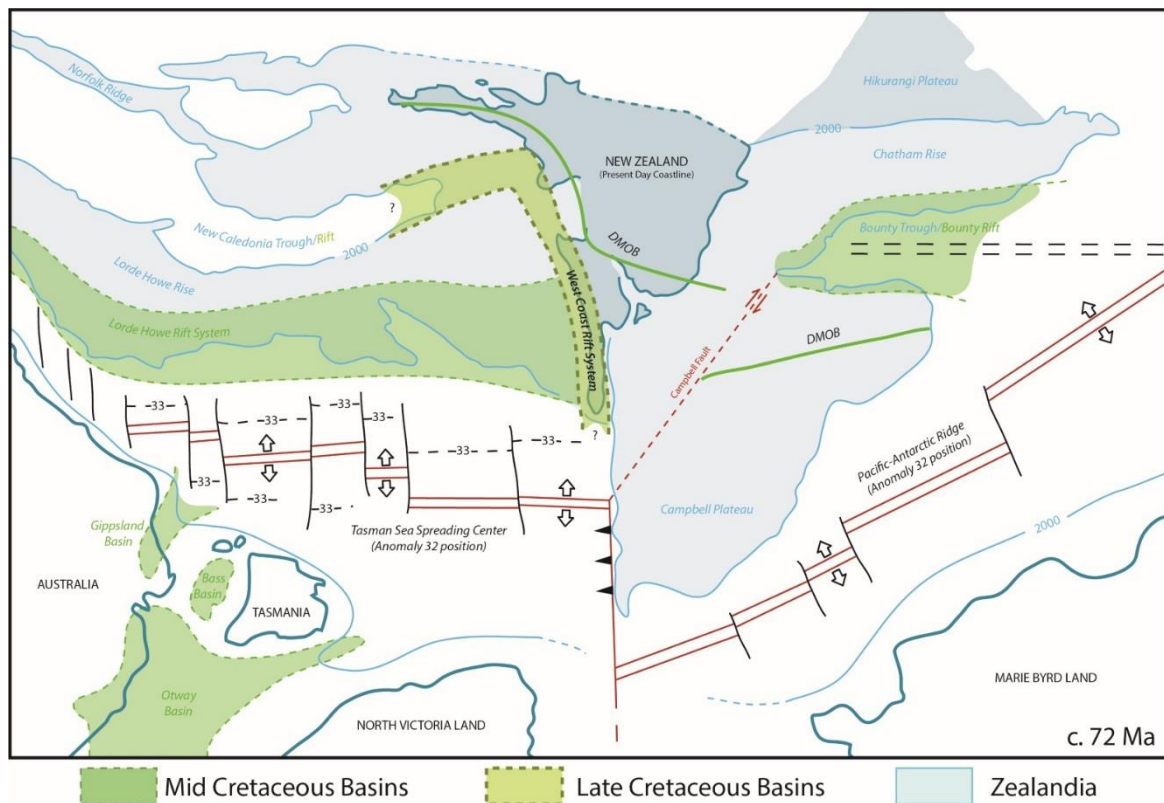


Figure 5.6: Plate reconstruction for anomaly 32 time (c. 72 Ma) with approximate zones of Mid- and Late Cretaceous rifts (modified from Kamp, 1986b and Laird, 1994). Note that the Tasman Sea Spreading center is spreading faster than the Pacific-Antarctic Ridge thus through the Westland region and north to Taranaki there is an inferred transtensional or strike-slip regime.

For the Middle Eocene Brunner Coal Measures, there is no evidence for reactivation of core complex faults, despite this time being inferred as the beginning of major continental extension. It is my interpretation that such processes may occur, but they are too slight to be recognized. Thickening in the Late Eocene and Oligocene from reactivation of the core complex faults is minor (100's of meters) (Riordan et al., 2014) in comparison to the major E-W extension responsible for the formation of the Paparoa Trough (1000's of meters). As the thicknesses of

the BCM barely approach 50m, using the above ratio, the influence of reactivation on deposition would be evidenced by only 5-10m of thickness variation, far too minor to be confidently recognized. For this reason, reactivation during the Middle Eocene is not ruled out, but for all intents and purposes it will not be noticeable in the sedimentary record.

## **5.5. Conclusions**

Study of the Brunner Coal Measures and their basal contact has provided new information regarding the geological evolution of the North Westland region through the Late Palaeocene to the Middle Eocene. Between the three regions (Buller, Charleston and Greymouth) examined during this thesis, there are noticeably different local tectonic and depositional histories. On a regional scale however, these are inherently linked with one another.

The Late Palaeocene – Early Eocene landscape of North Westland has previously been described as a period of total tectonic quiescence, peneplanation and prolonged subaerial chemical weathering. The latter two conclusions are also reached in this study. However, new evidence from Mt. Rochfort in the Buller Coal Field and reinterpretation of the Palaeocene stratigraphy in the Greymouth Basin suggests that tectonic quiescence was limited to only a few million years. Additionally, while of low gradient, the landscape included prominent highs where deposition did not commence for some time after the initial formation of the Brunner Coal Measures.

The three regions focused on in this study show three distinct styles of control on deposition of the Brunner Coal Measures. Remnant topography from older Late Cretaceous basins controlled deposition of the Brunner Coal Measures and the time coeval Island Sandstone in the Greymouth Basin. Marine transgression occurred here much earlier than elsewhere as the existing basin represented a low point in the landscape and was flooded preferentially. Similarly, the Buller Basin in the north of the study area is also flooded earlier than elsewhere. This though is attributed to small scale syndepositional faulting and the resultant subsidence. The Brunner Coal Measures in the remaining Charleston region are interpreted to have been deposited in a back stepping coastal plain related solely to the marine transgression. For the majority of Charleston region, the BCM are distinctly thinner and younger than their equivalents in the Greymouth and Buller Basins.

Palaeogeographic interpretations and the tectono-sedimentary model constructed from these, show that the landscape throughout the Late Palaeocene – Middle Eocene was structurally controlled. Deposition of the BCM and the following marine transgression is influenced by NNE trending faults known to be active during extension of the Challenger Rift System. The BCM represent the inception of this rift system in its initial stage of small scale disconnected faulting.



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## Appendix 1

Lithology logs for WB1, Addisons Flat exploratory drill hole from Solid Energy (curtesy of Stu Henley)

Drillhole WB1		West Buller EP 40 647		ABF 17 May 05	
Lithology Log					
From (m)	To (m)	Thick (m)	Code	Description	Notes
0.00	16.00	16.00	ALUV	Washedrilled: no core, (Quaternary gravels).	Cased to 16.00m through gravels.
16.00	298.90	282.90	SS	Sandstone: muddy, dk bu gy to med gy, v f/gr, occ f/gr, variably-sorted, quartzose, micaceous, sl calc, often with fine shell fragments, (Bluebottom Group).	Open hole drilled with HQ stratapax bit: log based on wash samples.
298.90	300.90	2.00	SS	Sandstone: v f/gr, dk gy, muddy, v weak, qtz, mica, well-sorted, not visibly calc, rare decayed shell frags.	HQ spot core.
300.90	301.00	0.10	NC	Core loss.	
301.00	454.80	153.80	SS	Sandstone, as for 16.0 - 298.90m: coarse, loose & quartzose @ approx 400m.	Open hole drilled with HQ stratapax bit.
454.80	456.40	1.60	SS	Sandstone: v f/gr & muddy, med gy, qtz, weak to v weak, occ mica flakes, with layers of coarse loose qtz sand in basal 40cm.	NQ spot core.
456.40	649.10	192.70	SS	Sandstone, as for 16.0 - 298.90m: with freq Fe-stained clasts below 460m, bec creamy bn, mod calc & silty twds assumed grad base on:	Open hole drilled with NQ stratapax bit: log based on wash samples.
649.10	671.30	22.20	LIME	Limestone: mod dev bdd 0-20°, sandy, wh to pa gy, with v f/gr to f/gr qtz sand in freq layers to 4cm thick, rock broken with handling on undulating sand layers @ 3-50cm spacing with v f/gr glauconite, mod strong, hard, but weak & fissile 658.68-659.0m, bec strong, silty & gy bn with few breaks @ 663.27-665.88m, occ shell hash layers, freq v coarse qtz xtals, some microcrystalline bands below 670.5m, "flaggy", (Waitakere Limestone).	NQ cored from 649.1m.

Drillhole WB1		West Buller EP 40 647			ABF 17 May 05	
Lithology Log						
From (m)	To (m)	Thick (m)	Code	Description	Notes	
671.30	675.90	4.60	<b>LIME</b>	Limestone: massive, coarse chips, wh to gy wh, mod strong with freq v weak layers adj to 0° breaks, rare v f/gr glauconitic specks, rare pa bn shell frags, occ v coarse qtz xtals, then with suspended coarse granules to small pebbles of sun-angular to rounded dk gy qtz @ 673.15-673.7m, (occ plucked from core), occ shell hash & fossil frags, grad contact to:		
675.90	694.57	18.67	<b>LIME</b>	Limestone, as above for 649.1-671.3m: flaggy, hard, strong, broken by hand @ 3-53cm spacing on glauconitic sand layers, scattered granules of dk gy qtz till 680m, occ swirling weak to mod weak wh highly-calc bands to 2cm thick, bec paler gy wh with depth, flaggy sub-horizontal joints/sand layers bec more cloely-spaced with depth: 1-3cm bdd, striated sharp basal contact.		
694.57	695.28	0.71	<b>GNS</b>	Gneiss: foliated, quartz-plagioclase-biotite, f/gr to med/gr, very strong.	Interpreted as boulder contained in basal limestone.	
695.28	695.80	0.52	<b>CG</b>	Conglomerate: v coarse, pebbles to cobbles of sub-rounded to rounded gneiss supported in matrix of f/gr limestone with qtz grains & glauconite, wh, strong, sharp erosional base @ 25°.	Basal limestone supporting detrital clasts of basement gneiss.	
695.80	702.90 EOH	7.10	<b>GNS</b>	Gneiss: foliated @ 25-55°, quartz-plagioclase-biotite, f/gr to med/gr, very strong to extremely strong, streaked gy wh/gy bn, bec paler & with muscovite below 700m, also irreg steep to sub-vertical fractures @ 10-20cm spacing, v pa gy wh in basal 20cm, (no biotite), (Charleston Metamorphic Group).	Basement.	

## Appendix 2

Drill hole logs Tk-19 and Tk-17 used in the Te Kuha – Mt. Rochfort transect (curtesy of CRL Energy, on behalf of Stevenson Mining Ltd)

Tk-17

0	0.43	0.43	Brunner Coal Measures	Top Soil
0.43	1	0.57	Brunner Coal Measures	Very Coarse Sandstone
1	1.4	0.4	Brunner Coal Measures	Underground Void
1.4	2.31	0.91	Brunner Coal Measures	Very Coarse Sandstone
2.31	2.47	0.16	Brunner Coal Measures	Lost Core
2.47	2.52	0.05	Brunner Coal Measures	Wood
2.52	4.05	1.53	Brunner Coal Measures	Very Coarse Sandstone
4.05	7.4	3.35	Brunner Coal Measures	Underground Void
7.4	7.52	0.12	Brunner Coal Measures	Very Coarse Sandstone
7.52	7.6	0.08	Brunner Coal Measures	Mudstone
7.6	8	0.4	Brunner Coal Measures	Very Coarse Sandstone
8	9.15	1.15	Brunner Coal Measures	Underground Void
9.15	10.55	1.4	Brunner Coal Measures	Very Coarse Sandstone
10.55	10.75	0.2	Brunner Coal Measures	Lost Core
10.75	12.05	1.3	Brunner Coal Measures	Very Coarse Sandstone
12.05	12.22	0.17	Brunner Coal Measures	Mudstone
12.22	15.82	3.6	Brunner Coal Measures	Very Coarse Sandstone
15.82	16.33	0.51	Brunner Coal Measures	Underground Void
16.33	19.66	3.33	Brunner Coal Measures	Very Coarse Sandstone
19.66	20.82	1.16	Brunner Coal Measures	Underground Void
20.82	22.25	1.43	Brunner Coal Measures	Very Coarse Sandstone
22.25	22.55	0.3	Brunner Coal Measures	Coarse Sandstone
22.55	24.58	2.03	Brunner Coal Measures	Very Coarse Sandstone
24.58	25.3	0.72	Brunner Coal Measures	Very Coarse Sandstone
25.3	26	0.7	Brunner Coal Measures	Underground Void
26	26.24	0.24	Brunner Coal Measures	Very Coarse Sandstone
26.24	26.8	0.56	Brunner Coal Measures	Coarse Sandstone
26.8	29.55	2.75	Brunner Coal Measures	Very Coarse Sandstone
29.55	29.77	0.22	Brunner Coal Measures	Underground Void
29.77	30.04	0.27	Brunner Coal Measures	Coarse Sandstone
30.04	30.18	0.14	Brunner Coal Measures	Very Coarse Sandstone
30.18	30.51	0.33	Brunner Coal Measures	Coarse Sandstone
30.51	31.72	1.21	Brunner Coal Measures	Very Coarse Sandstone
31.72	32.3	0.58	Brunner Coal Measures	Underground Void
32.3	33.95	1.65	Paparoa Coal Measures	Mudstone
33.95	34.25	0.3	Paparoa Coal Measures	Fine Sandstone
34.25	35	0.75	Paparoa Coal Measures	Underground Void
35	36.4	1.4	Paparoa Coal Measures	Fine Sandstone
36.4	36.79	0.39	Paparoa Coal Measures	Mudstone
36.79	38.43	1.64	Paparoa Coal Measures	Pebble Conglomerate
38.43	38.87	0.44	Paparoa Coal Measures	Fine Sandstone
38.87	39.1	0.23	Paparoa Coal Measures	Coarse Sandstone
39.1	39.4	0.3	Paparoa Coal Measures	Lost Core
39.4	39.44	0.04	Paparoa Coal Measures	Coarse Sandstone

39.44	39.66	0.22	Paparoa Coal Measures	Mudstone
39.66	40.81	1.15	Paparoa Coal Measures	Coarse Sandstone
40.81	40.94	0.13	Paparoa Coal Measures	High Carb Mudstone
40.94	41.42	0.48	Paparoa Coal Measures	Coarse Sandstone
41.42	41.54	0.12	Paparoa Coal Measures	High Carb Mudstone
41.54	42.1	0.56	Paparoa Coal Measures	Coarse Sandstone
42.1	43.7	1.6	Paparoa Coal Measures	Fine Sandstone
43.7	44.51	0.81	Paparoa Coal Measures	Mudstone
44.51	45.1	0.59	Paparoa Coal Measures	Fine Sandstone
45.1	45.95	0.85	Paparoa Coal Measures	Mudstone
45.95	46.4	0.45	Paparoa Coal Measures	Fine Sandstone
46.4	47	0.6	Paparoa Coal Measures	Fine Sandstone
47	48.9	1.9	Paparoa Coal Measures	Fine Sandstone
48.9	51.68	2.78	Paparoa Coal Measures	Medium Sandstone
51.68	53.53	1.85	Paparoa Coal Measures	Granule Conglomerate
53.53	57.55	4.02	Paparoa Coal Measures	Medium Sandstone
57.55	57.75	0.2	Paparoa Coal Measures	Lost Core
57.75	59.1	1.35	Paparoa Coal Measures	Medium Sandstone
59.1	67.78	8.68	Paparoa Coal Measures	Medium Sandstone
67.78	68.9	1.12	Paparoa Coal Measures	Very Fine Sandstone
68.9	69.2	0.3	Paparoa Coal Measures	Lost Core
69.2	72.72	3.52	Paparoa Coal Measures	Very Fine Sandstone
72.72	78.8	6.08	Paparoa Coal Measures	Granule Conglomerate
78.8	78.9	0.1	Paparoa Coal Measures	Lost Core
78.9	88.28	9.38	Paparoa Coal Measures	Granule Conglomerate
88.28	93.59	5.31	Paparoa Coal Measures	Medium Sandstone
93.59	96.45	2.86	Paparoa Coal Measures	Granule Breccia
96.45	96.7	0.25	Paparoa Coal Measures	Lost Core
96.7	98.3	1.6	Paparoa Coal Measures	Granule Breccia
98.3	98.5	0.2	Paparoa Coal Measures	Lost Core
98.5	99.2	0.7	Paparoa Coal Measures	Medium Sandstone
99.2	100.96	1.76	Hawks Crag Breccia	Pebble Breccia
100.96	102.44	1.48	Hawks Crag Breccia	Very Coarse Sandstone
102.44	103.79	1.35	Hawks Crag Breccia	Pebble Breccia
103.79	105.1	1.31	Hawks Crag Breccia	Medium Sandstone
105.1	105.3	0.2	Hawks Crag Breccia	Lost Core
105.3	113.5	8.2	Hawks Crag Breccia	Granule Breccia
113.5	114.35	0.85	Hawks Crag Breccia	Granite – coarse grained
114.35	114.45	0.1	Hawks Crag Breccia	Shear Zone
114.45	115.75	1.3	Hawks Crag Breccia	Pebble Breccia
115.75	115.8	0.05	Hawks Crag Breccia	Shear Zone
115.8	144.5	28.7	Hawks Crag Breccia	Pebble Breccia

Tk-19 (coal thickness, quality and roof and floor separation removed for confidentiality)

0	0.3	0.3	Brunner Coal Measures	Lost Core
0.3	0.4	0.1	Brunner Coal Measures	Top Soil
0.4	1.6	1.2	Brunner Coal Measures	Lost Core
1.6	2.1	0.5	Brunner Coal Measures	Underground Void
2.1	2.38	0.28	Brunner Coal Measures	Very Coarse Sandstone
2.38	2.63	0.25	Brunner Coal Measures	Lost Core
2.63	4.53	1.9	Brunner Coal Measures	Very Coarse Sandstone
4.53	4.93	0.4	Brunner Coal Measures	Lost Core
4.93	8.91	3.98	Brunner Coal Measures	Very Coarse Sandstone
8.91	9.67	0.76	Brunner Coal Measures	Siltstone
9.67	10.25	0.58	Brunner Coal Measures	Lost Core
10.25	11.5	1.25	Brunner Coal Measures	Very Fine Sandstone
11.5	12.1	0.6	Brunner Coal Measures	Lost Core
12.1	12.56	0.46	Brunner Coal Measures	Very Fine Sandstone
12.56	12.68	0.12	Brunner Coal Measures	Mudstone
12.68	12.9	0.22	Brunner Coal Measures	Mudstone
12.9	13.8	0.9	Brunner Coal Measures	Lost Core
13.8	14.4	0.6	Brunner Coal Measures	Fine Sandstone
14.4	14.55	0.15	Brunner Coal Measures	Lost Core
14.55	16.56	2.01	Brunner Coal Measures	Very Fine Sandstone
16.56	16.74	0.18	Brunner Coal Measures	Mud
16.74	18.75	2.01	Brunner Coal Measures	Mudstone
18.75	19.3	0.55	Brunner Coal Measures	Lost Core
19.3	20.9	1.6	Brunner Coal Measures	Mudstone
26.72	27.32	0.6	Brunner Coal Measures	Fine Sandstone
27.32	27.7	0.38	Brunner Coal Measures	Mudstone
27.7	28.15	0.45	Brunner Coal Measures	Lost Core
28.15	28.83	0.68	Brunner Coal Measures	Carb Mudstone
28.83	30.8	1.97	Brunner Coal Measures	Fine Sandstone
30.8	35.14	4.34	Brunner Coal Measures	Very Coarse Sandstone
35.14	36.1	0.96	Brunner Coal Measures	Lost Core
36.1	39.66	3.56	Brunner Coal Measures	Very Coarse Sandstone
39.66	40.82	1.16	Brunner Coal Measures	Very Coarse Sandstone
40.82	41.46	0.64	Brunner Coal Measures	Granule Conglomerate
41.46	41.54	0.08	Brunner Coal Measures	Pebble Conglomerate
41.54	41.8	0.26	Brunner Coal Measures	Very Fine Sandstone
41.8	44.77	2.97	Brunner Coal Measures	Very Coarse Sandstone
44.77	44.9	0.13	Brunner Coal Measures	Lost Core
44.9	46.43	1.53	Brunner Coal Measures	Very Coarse Sandstone
46.43	46.61	0.18	Brunner Coal Measures	Lost Core
46.61	47.51	0.9	Brunner Coal Measures	Granule Conglomerate
47.51	48.4	0.89	Brunner Coal Measures	Lost Core
48.4	49.65	1.25	Brunner Coal Measures	Granule Conglomerate
49.65	49.69	0.04	Brunner Coal Measures	High Carb Mudstone
49.69	50.7	1.01	Brunner Coal Measures	Lost Core
50.7	51.2	0.5	Brunner Coal Measures	Mudstone
51.2	52.3	1.1	Brunner Coal Measures	Granule Conglomerate
52.3	52.72	0.42	Brunner Coal Measures	Lost Core
52.72	55.18	2.46	Brunner Coal Measures	Very Coarse Sandstone
55.18	55.31	0.13	Brunner Coal Measures	Fine Sandstone

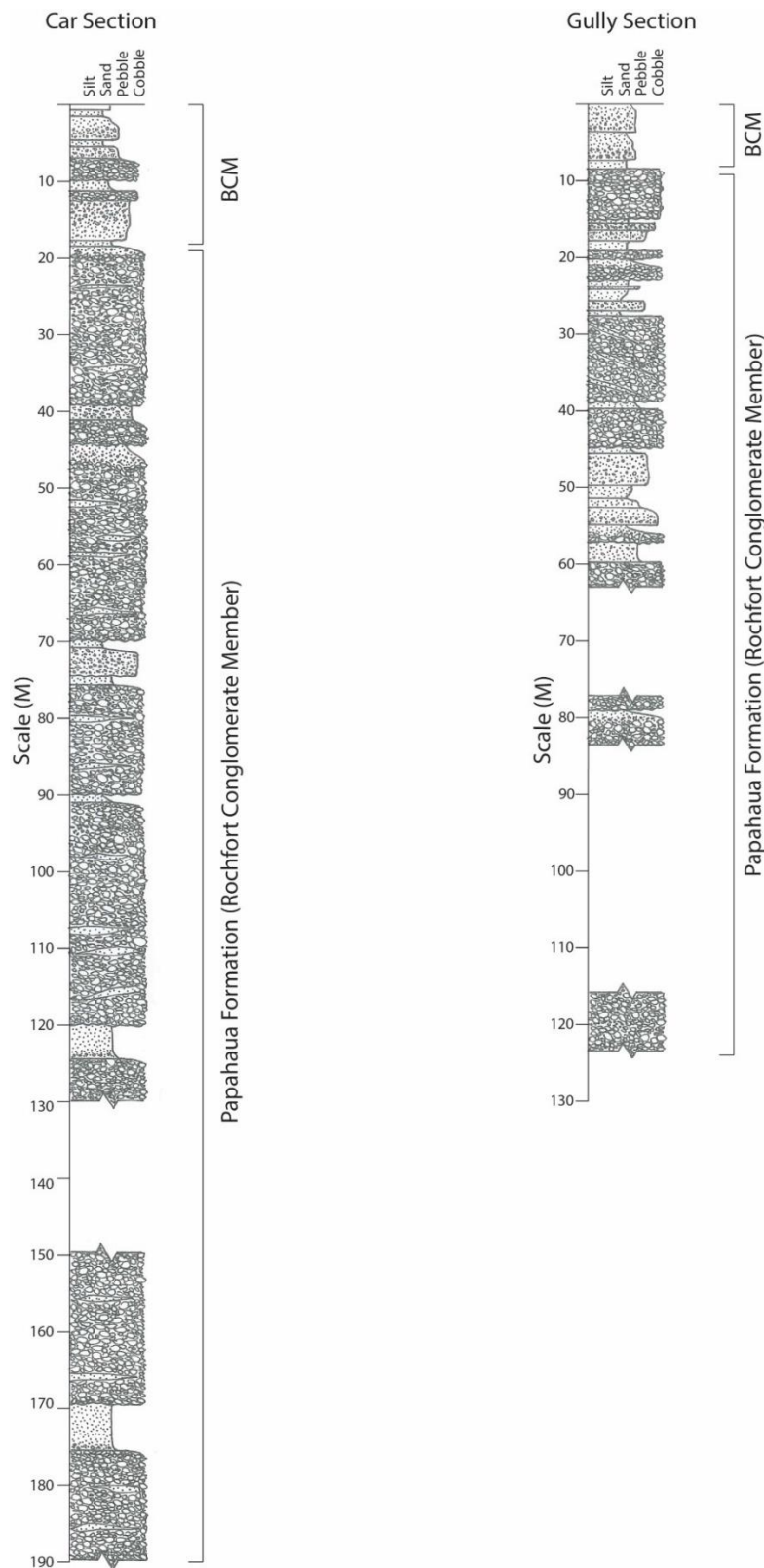
55.31	55.46	0.15	Brunner Coal Measures	Lost Core
55.46	55.92	0.46	Brunner Coal Measures	Fine Sandstone
55.92	57.56	1.64	Brunner Coal Measures	Very Coarse Sandstone
57.56	58.25	0.69	Brunner Coal Measures	Pebble Conglomerate
58.25	61.85	3.6	Brunner Coal Measures	Very Fine Sandstone
61.85	62.4	0.55	Brunner Coal Measures	Very Coarse Sandstone
62.4	64.53	2.13	Brunner Coal Measures	Granule Conglomerate
64.53	66.3	1.77	Brunner Coal Measures	Pebble Conglomerate
66.3	66.5	0.2	Brunner Coal Measures	Lost Core
66.5	67.21	0.71	Paparoa Coal Measures	Pebble Conglomerate
67.21	67.43	0.22	Paparoa Coal Measures	Granule Conglomerate
67.43	67.5	0.07	Paparoa Coal Measures	Lost Core
67.5	69.83	2.33	Paparoa Coal Measures	Granule Conglomerate
69.83	70	0.17	Paparoa Coal Measures	Mudstone
70	70.4	0.4	Paparoa Coal Measures	Lost Core
70.4	70.97	0.57	Paparoa Coal Measures	Mudstone
70.97	71.1	0.13	Paparoa Coal Measures	Lost Core
71.1	71.9	0.8	Paparoa Coal Measures	Mudstone
71.9	72.15	0.25	Paparoa Coal Measures	Lost Core
72.15	73.75	1.6	Paparoa Coal Measures	Mudstone
73.75	80.23	6.48	Paparoa Coal Measures	Granule Conglomerate
80.23	80.75	0.52	Paparoa Coal Measures	Lost Core
80.75	82.5	1.75	Paparoa Coal Measures	Very Coarse Sandstone
82.5	82.8	0.3	Paparoa Coal Measures	Lost Core
82.8	84.6	1.8	Paparoa Coal Measures	Very Coarse Sandstone
84.6	84.83	0.23	Paparoa Coal Measures	Lost Core
84.83	87.8	2.97	Paparoa Coal Measures	Very Fine Sandstone
87.8	88.24	0.44	Paparoa Coal Measures	Very Coarse Sandstone
88.24	90.41	2.17	Paparoa Coal Measures	Fine Sandstone
90.41	90.74	0.33	Paparoa Coal Measures	Granule Breccia
90.74	90.82	0.08	Paparoa Coal Measures	Lost Core
90.82	93.82	3	Paparoa Coal Measures	Coarse Sandstone
93.82	94.03	0.21	Paparoa Coal Measures	Lost Core
94.03	94.28	0.25	Paparoa Coal Measures	High Carb Mudstone
94.28	101.5	7.22	Paparoa Coal Measures	Very Coarse Sandstone
101.5	101.7	0.2	Paparoa Coal Measures	Lost Core
101.7	108.15	6.45	Paparoa Coal Measures	Granule Conglomerate
108.15	108.28	0.13	Paparoa Coal Measures	Lost Core
108.28	115.34	7.06	Paparoa Coal Measures	Coarse Sandstone
115.34	115.44	0.1	Paparoa Coal Measures	Lost Core
132.61	132.91	0.3	Paparoa Coal Measures	Lost Core
132.91	134.39	1.48	Paparoa Coal Measures	Granule Conglomerate
134.39	137.74	3.35	Paparoa Coal Measures	Siltstone
137.74	142.58	4.84	Paparoa Coal Measures	Granule Conglomerate
142.58	142.65	0.07	Paparoa Coal Measures	Lost Core
142.65	144.66	2.01	Paparoa Coal Measures	Granule Conglomerate
144.66	145.51	0.85	Paparoa Coal Measures	Mudstone
145.51	145.8	0.29	Paparoa Coal Measures	Shear Zone
145.8	145.86	0.06	Paparoa Coal Measures	Lost Core
145.86	155.7	9.84	Paparoa Coal Measures	Granule Conglomerate
155.7	155.75	0.05	Paparoa Coal Measures	Lost Core
155.75	158.69	2.94	Paparoa Coal Measures	Granule Conglomerate

158.69	159.5	0.81	Paparoa Coal Measures	Shear Zone
159.5	160.58	1.08	Paparoa Coal Measures	Granule Conglomerate
160.58	160.68	0.1	Paparoa Coal Measures	Lost Core
160.68	161.5	0.82	Paparoa Coal Measures	Granule Conglomerate
161.5	161.55	0.05	Paparoa Coal Measures	Lost Core
161.55	164.15	2.6	Paparoa Coal Measures	Granule Conglomerate
164.15	164.3	0.15	Paparoa Coal Measures	Lost Core
164.3	165.41	1.11	Paparoa Coal Measures	Very Fine Sandstone
165.41	165.56	0.15	Paparoa Coal Measures	Lost Core
165.56	169.21	3.65	Paparoa Coal Measures	Granule Conglomerate
169.21	171.06	1.85	Paparoa Coal Measures	Pebble Breccia
171.06	171.63	0.57	Hawks Crag Breccia	Shear Zone
171.63	171.9	0.27	Hawks Crag Breccia	Medium Sandstone
171.9	175.6	3.7	Hawks Crag Breccia	Pebble Breccia
175.6	175.7	0.1	Hawks Crag Breccia	Lost Core
175.7	178.48	2.78	Hawks Crag Breccia	Pebble Breccia
178.48	178.6	0.12	Hawks Crag Breccia	Lost Core



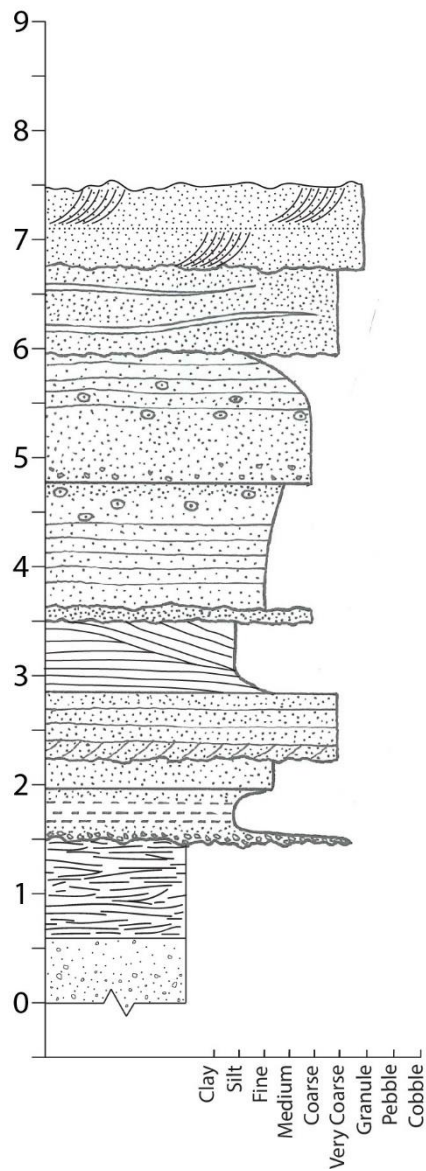
### Appendix 3

Stratigraphic columns, Mt Rochfort sections used in Mt Rochfort – Te Kuha transect

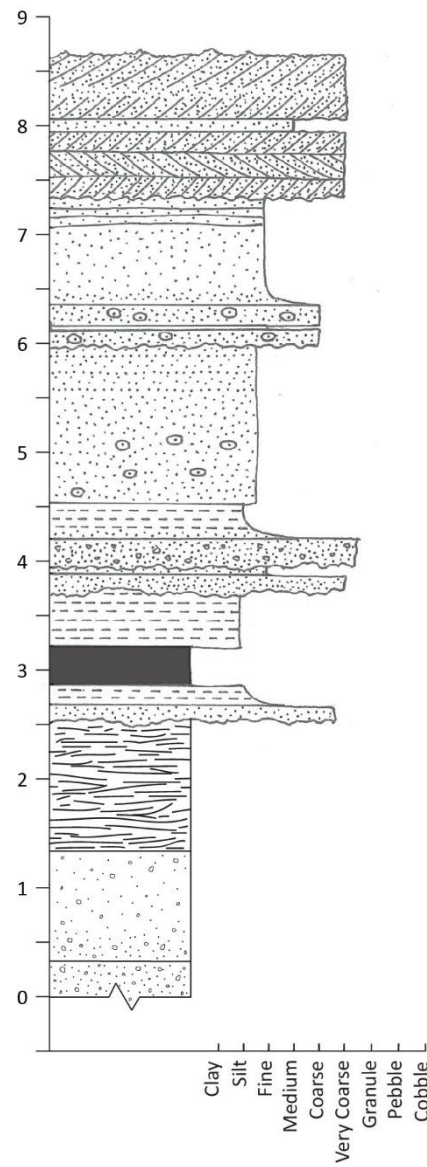


Measured sections used in construction of the Coalbrookdale lithofacies transect (un-interpreted)

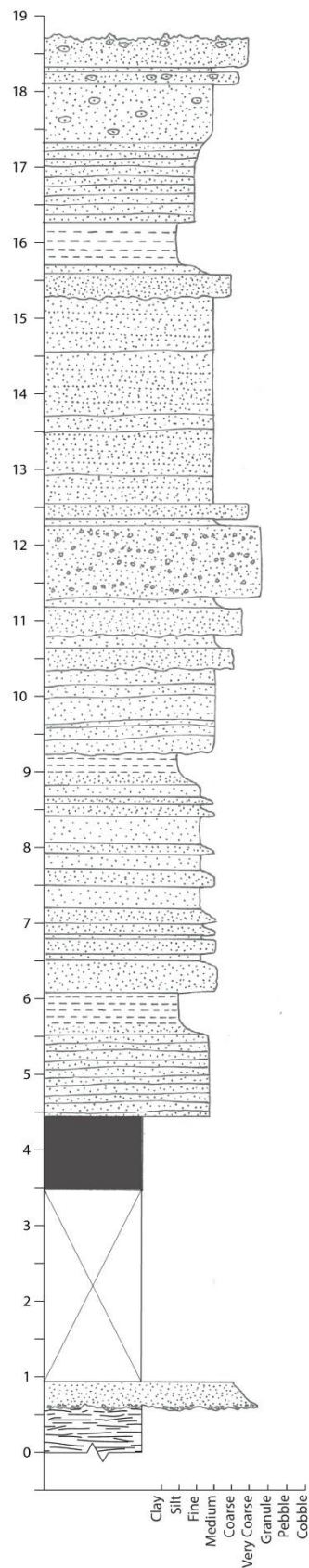
Headwaters section



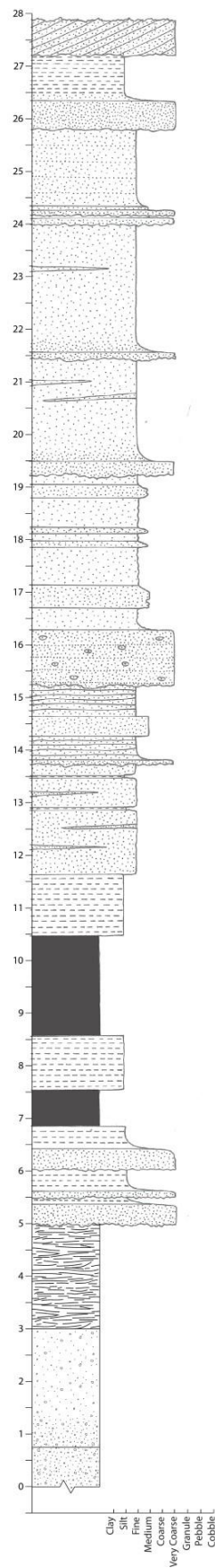
## Cliff section



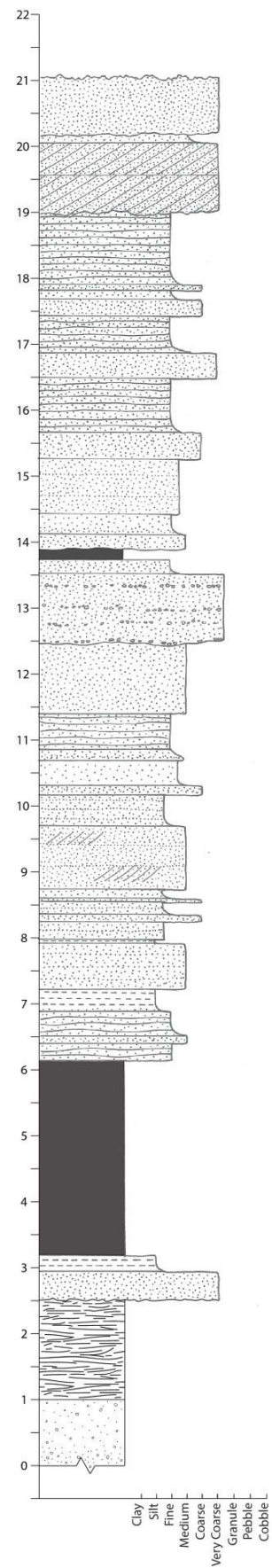
# Creek section



## Old mines section

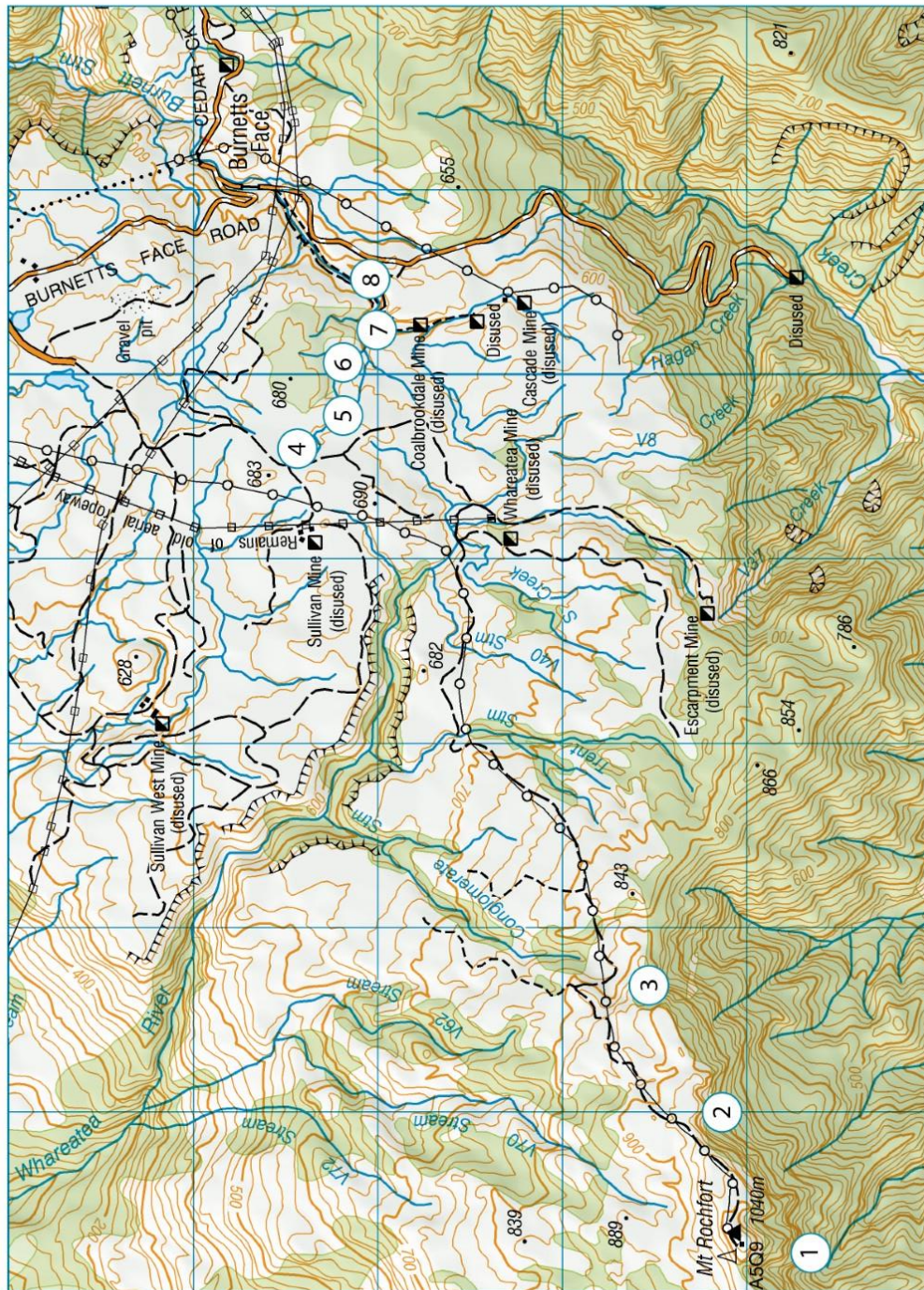


## Roadcut section





# Section Map for Mt Rochfort and Coalbrookdale, Denniston Plateau, Buller Coalfield.



## Sections

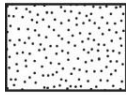
1. Mt Rochfort
2. Car
3. Gully
4. Headwaters
5. Cliff
6. Creek
7. Old Mines
8. Roadcut

## Appendix 4

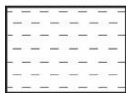
### Key for stratigraphic columns

### Stratigraphic Column Textural Key

#### Sedimentary Textures



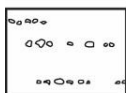
Sandstone



Siltstone



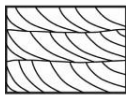
Conglomerate



Granules



Sedimentary Breccia



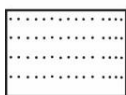
Planar Cross Bedding



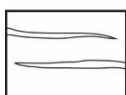
Trough Cross Bedding



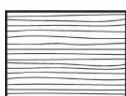
Lateral Accretion Surfaces/  
Foreset Laminations



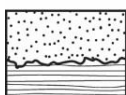
Faint Bedding



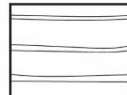
Lenses



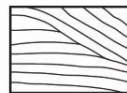
Carbonaceous Laminations



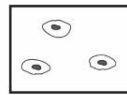
Erosional Surfaces



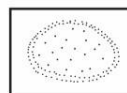
Paired Mud Drapes



Deformation



Iron Concretions



Siliceous Concretions



Coal



Silty Coal

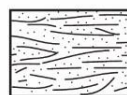


Coaly Fragments/Stringers

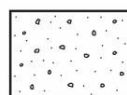


Unconformity

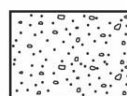
#### Weathering Profile



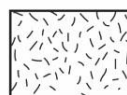
Friable Clay



Quartz Fragments in Clay



Hyalodacite



Granite